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COMBINING THE FUNCTIONALITY OF MULTIPLE AUTOMATIC CELLS BY INTRODUCING A DUAL-ARM ROBOT STATION

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ABSTRACT

Saigopal Vasudevan: Combining the functionality of multiple automatic cells by introducing a dual-arm robot station
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The industrial revolution 4.0 is resulting in a shift of production and manufacturing processes to become more efficient and streamlined. This involves the refurnishing and upgrading of existing technology in production lines. Significant research done in the field of dual-arm robot manipulators shows us that anthropomorphic robots can be used interchangeably or replace humans, without major changes to the workplace, resulting in low cost, flexible automation and increased functionality. This thesis implementation aims to merge the functionalities of two automatic workstations by upgrading the elements of one of the workstations and removing the other workstation from the line. Based on the available resources and existent in-lab facilities, the prime objective is to determine the most efficient means to utilize a dual-arm manipulator to combine and update the functionalities of these two individual cells. And, how best to create exposure, by demonstrating the operations and features of the relatively unacquainted breed of industrial robots to new generations of students. This thesis focuses on the virtual implementation of the dual-arm station and the process flow is modelled and simulated, as proof of concept. The physical implementation would be carried out subsequently.

Based on an extensive analysis of relevant literature, manipulator capabilities, in-house fabrication and purchasing feasibilities; the most efficient implementation was made after multiple iterative changes in cell and tooling design, and the process was created using the offline programming tool. The created dual-arm cell has replaced two individual robot manipulators and additional conveyor systems and acts as both, a production and an Automatic Storage and Retrieval System (AS/RS) unit, additionally it enables the intelligent production line (where the cell is being installed) to interact with other isolated intelligent systems in the laboratory. The introduced changes to the production line have increased its functionality, while removing obsolete equipment. The production efficiency is increased while reducing the space utilized and demonstrates the operation of a dual-arm industrial robots. Future works to improve the operations in the cell may include using anthropomorphic hands as tooling and utilizing intelligent vision systems to additionally handle deformable linear objects for the REMODEL project of the Horizon 2020 research and innovation programming, while still serving its originally intended purpose in the intelligent production line.

Keywords: Dual-arm robots, discrete intelligent assembly line, modelling, Offline Robot Programming, process planning and optimization, material handling

The originality of this thesis has been checked using the Turnitin Originality Check service.

PREFACE

First and foremost my appreciation and gratitude goes to my family, for none of this would have been possible without their faith and belief in me and my abilities. They provided the support and love required to do a masters in Finland, where there is so much emphasis placed on personal well-being and opportunities for young professionals and students.

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Thirdly, I would like to thank all of my fellow researchers and colleagues, but more importantly Ronal Bejarano and Antonios Sylari, who were and currently are working alongside me in FAST-Lab. It was truly an honour to work alongside and learn from them and the bond created is truly, a remarkable one.

Finally, I would like to thank all of my friends and well-wishers here in Tampere. I would like to specially mention Ahalya Ganesh, Hari Nagarajan, Suraj Panickar, and Hazel who are practically my family here. Life here would have been starkly different and drab without their presence in my life.

Looking forward to having my thesis read by all of you and hopefully by many other people.

Yours truly,

Saigopal Vasudevan

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

FMS	Flexible Manufacturing Systems
SPM	Special Purpose Machines
CPS	Cyber-physical Systems
CPPS	Cyber-physical Production Systems
I/O	Input/ Output
WS	Work Station
DOF	Degrees of Freedom
SCARA	Selective-Compliance-Articulated Robot Arm
EOAT	End of Arm Tool
PLC	Programmable Logic Controller
SME	Small and Medium-sized Enterprises
AS/RS	Automatic Storage and Retrieval System
RTU	Remote Terminal Unit
DPWS	Device Profile for Web Services
ST	Structured Text
REST	Representational State Transfer
SOAP	Simple Object Access Protocol
XML	eXtensible Markup Language
MSD	Magnetic Switchable Devices
Cobot	COllaborative roBOT
ATC	Automatic Tool Changer
LHS	Left Hand Side
RHS	Right Hand Side
UML	Unified Modelling Language
AMiR	Autonomous Mobile industrial Robot
DLO	Deformable Linear object
REMODEL	Robotic tEchnologies for the Maipulation of cOmplex DeformablE Linear objects

1. INTRODUCTION

This portion of the document focuses on the primary concepts that the reader must comprehend in order to understand the framework which forms the basis of this document. The aim of this section is to make the reader familiar with the scope of this Master Thesis and the plan of action to solve the challenges faced.

1.1 Thesis background

The usage of robotics has exponentially increased over the last two decades. Industrial robots have significantly improved in functionality and have become more accessible to all the levels of the industry. The utilization of robots in manufacturing and production industries is no longer restricted to the large scale companies. The evolution of Flexible Manufacturing Systems (FMS) have radicalized the utilization of robots by medium and small scale Industries, as stated by [1]. The FMS cells utilize robots as a standalone unit or in combination with other Special Purpose machines (SPM) with varying natures of operation. The majority of the existing FMS belonging to the period of the third industrial revolution (Digital Revolution) were still labour dependent to a certain degree, resulting in increased overheads, mainly in the aspect of production times. A direct result of the above, was increased operational and production costs. This created the requirement for more streamlined and autonomous operation of these automated systems. [2]

The dawn of industry 4.0 has made manufacturing systems more intelligent and highly interconnected, with the advent of the internet of things. The concept of Smart Factories, wherein, all the elements of the production system are equipped with sensors which relay real-time data to intelligent control systems that make autonomous decisions based on sensor data is one of the major outcomes, was highlighted in [3]. Another outcome is the creation of Cyber-physical Systems (CPS) which merges the physical and digital variables of the system, to an extent where it cannot be differentiated in a reasonable way anymore, is a concept described by [4]. The development of Knowledge based and orchestration services enable manufacturing systems to become more flexible and adaptive to change, this further aids the autonomism of manufacturing systems and was extensively researched and documented by [5].

The current trends in the industry, is to update the existing manufacturing systems and models of production, to meet the standards and practises of the current industrial revolution. This is rapidly becoming a must-do in order for the company to thrive in the current economic scenario and stay in pace with the competition. Growth and development is a phenomenon which may stagnate, but never ceases to progress. And with new solutions and technologies being introduced, there is never a dearth of scopes which require improvement.

1.2 Problem statement

The previous section emphasises the constant changes in trends and the requirement for upgradation of existing technologies. The impact of the fourth industrial revolution and the current state of advancements in the development of bimanual manipulation in industrial robotics as proposed in [6] have brought about the special requirement for this particular implementation, which is my master’s thesis work.

The implementation and the demonstration of the work is performed in the main cell of the FASTory line, which is an integral part of FAST-Lab [7]. The FASTory line is the equivalent of a real-time intelligent production line and it replicates the production of 27 individual components (keypad, frame and screen), which can be modularly used to create 729 combinations of the product (cellular phone) [8]. The production process is represented in the form of pictures being drawn on papers bound on pallets (representing the manufacturing mould) which is transported/ bypassed through all the cells in the production line, by means of a conveyor mechanism. [8]

The line has 12 individual automatic cells or work stations (WS), 10 of which are capable of producing the drawings of all the components and 2 special case cells which perform palletizing and paper handling operations, respectively. The essential outcome of this thesis work is to merge these two special case cells, namely the main cell (WS1) and the buffer cell (WS7). The buffer cell consists of an actuator with 3 DOF in the linear axes and a single DOF in rotation, which is used to automatically store/ retrieve the pallets. The main cell consists of a SCARA manipulator which is utilized to handle and replace the papers (representing the finished product) and a slider mechanism which is used to transfer the product out of the cell.

The thesis work requires the functionalities of these two cells to be combined by utilizing a Dual-arm robot and replacing the existing actuation systems present in these individual cells. Additionally, there is an expansion in the use cases and capabilities of the FASTory line wherein it interacts with a mobile robot. The capabilities and scope of the FASTory line as a whole are also expanded (explained in later chapters), though it is not a part of my scope of work, it is also a crucial factor for necessitating the requirement of the work to be done, which would be subsequently transformed into my thesis.

1.3 Objectives

The expected final outcome required of the thesis work are broadly stated in the preceding section. However, this can be considered as the final goal, which can be achieved by defining and satisfying a number of relevant objectives. The following lists document the various deliverables which have to be performed for the proper completion and commissioning of the thesis work.

- Finalizing a suitable model of the Bi-manual manipulator from Yaskawa, in [9], with an emphasis on the following characteristics suggested in [10].
  - Payload capabilities
  - Manipulator reachability
  - Degrees of Freedom
  - Sufficient I/O capabilities for the controller
  - Repeatability of operation
  - Manipulator Weight and Ingression Protection [10]
- Designing the work environment, merging the functionality of the two work stations.
  - Modifying the main cell structure to accommodate the robot manipulator
  - Repositioning the conveyor and increasing cell size to increase the manipulator work area and to accommodate the mobile robot
  - Setting up an array of racks for storing the pallet
  - Creating provisions for a paper feeder mechanism and basket storage
  - Allowing the manual storage of additional miscellaneous material for use in FASTory operations
- Designing the end of arm tooling (EOAT) for
  - Bi-manual manipulation of the pallet (Loading and Unloading)
  - Removing and Replacing the magnetic paper clamp of the pallet
  - Paper Handling (Removing and replacing the paper in the pallet)
  - Handling of the basket containing paper for the Mobile robot. Additionally,
  - Gripper/s selection for handling paper, paper clamp and basket
  - Developing a modular holder for easy addition/ replacement of EOATs.

- Creating the workstation environment in the Offline programming/ simulation tool MotoSim EG VRC
- Checking and re-evaluating the cell design and the points of interaction in the simulation software

1.4 Challenges and limitations

There were a multitude of challenges faced during the performance of this thesis. Some of them include:

- Incompatible 3D model file types of the original elements of the main and buffer cells, to work with SolidWorks. Greatly restricting the easy utilization of its modelling features.
- MotoSim has performance issues, especially because of the nature of licensing with a floating key, wherein it had to be connected directly (wired/ wirelessly) to the universities network, greatly influencing the plan for work allocation.
- All manuals provided for using the Yaskawa robots and MotoSim, were expressly prepared for working single arm robots. The information provided to work with dual arm robots is unclear or has to be extrapolated from other concepts which have little connection to each other.
- Feedback communication between the fabrication team regarding the designs and machining capabilities, increased the lead time for creating tooling and the cell structures.

1.5 Document structure

This document comprises of six chapters. The first chapter is the introduction to the thesis work, which outlines its framework. The second is the ‘State of the Art’ which provides a literature review of the relevant concepts and facilities, which provides the background knowledge to successfully implement the thesis. Following that is the chapter where the proposed Methodologies and the ideation of the solutions based on the research work done in the background. The fourth chapter describes in detail the various activities done during the implementation phase and the documentation of the subsequent findings and challenges The Final chapter in this thesis documents the conclusions drawn from this thesis and illustrates the future work which can be carried out to further improve the existing concepts.

2. STATE OF THE ART

This chapter documents all the relevant literature and the contemporary technologies which were referred to and utilized in the implementation of this thesis. It explains the concepts and their evolution, all of which will help provide the fundamental background required to understand the contents of this document.

There are five major sections presented in this portion of the document. The first section discusses about the various techniques by which Industrial robots can be programmed to perform the required operation, as it (robots) is one of the major actors in this implementation. The advent of dual-arm robots, their potential benefits and advantages they have over traditional single-arm industrial robots are discussed in the second section. The third section explains in detail about the relevant end of arm tooling concepts which were considered and their selection criteria for the particular application. The fourth section describes the intelligent manufacturing system in which these automatic production cells are an integral part, the capabilities and the functionalities of the FASTory line is documented here. The fifth and final section of this chapter would summarize the previously mentioned sections and will highlight the inter relationships between the same.

2.1 Programming of Industrial Robots

The usage of robots in manufacturing industries has exponentially increased over the last two decades. Industrial robots have significantly upgraded functionality and have become more accessible to all levels of the business. The advancement in technology and the attractive ROIs have made implementing these robots a profitable option, even for small/ medium scale production industries and industries, where extensive material handling is involved.

The introduction of a robot to an existing production line can be a very tricky task. It requires a significant capital investment in addition to preparatory work spent by individuals who specialize in electrical design, mechanical design, safety planning, etc. Additional costs are incurred due to interruptions in the production process due to system downtime (layout change, equipment modification, robot installation and programming) and efficient robot integration with a PLC or similar control element. These are just some of the hurdles put forth by [11].

This portion of the second chapter is discussing the prevalent methods currently being used in the programming of industrial robots. The first subsection focuses on the various aspects of online programming and the scenarios where it is used and the second subsection focuses on the various techniques involved in the offline programming industrial robotic systems. Each subsection would highlight and weigh the pros and cons of some of the existing methods and the final summary portion of the chapter would describe the method used in this implementation.

2.1.1 Online Programming

The grounds on which I categorized a particular method as online programming is the presence of the programmer near the actual robot environment. There are several methods through which online programming is implemented, they include:

- the usage of teaching pendant
- Lead-through programming
- Teaching by demonstration

Majority of all online robot programming is usually performed by highly skilled robot operators/ programmers by manually jogging the robot manipulator to the desired target locations and saving the position data, through a Teach Pendant. See Figure 1. The parameters of the path to be taken from one target location to the next, the orientation of the robot axes, the coordinate system being utilized for specific sets of operations, the I/O messages to be executed, collision avoidance between the elements in the workspace, the logic structure of the robot program in the case of errors, etc., are determined by the judgement and experience of the programmer. This results in the traditional online programming method to be a very time consuming task especially if the process or the geometry of the payload is complicated. This was highlighted and explained in [12]

The lack of intuitiveness, the risk to the operator/ programmer and the system down-time during the teaching process are some of the deterrents to using Teach Pendant method of programming. Downtime due to programming the robots by traditional online programming methods creates impractical overheads for the small and medium scale enterprises. Especially in the case of FMSs, a significant portion of the expenses for implementing robots, is its programming costs. This is mainly because, production grade robot systems require days to weeks of work by skilled robot programmers, contingent with the nature of the application. [11]

***Figure 1** Teach Pendant Yaskawa Motoman robots*

Lead-through programming methodologies were introduced to overcome the aforementioned deterrents of teaching through a Teach Pendant. It provides a more intuitive platform for efficient discrete target or continuous path teaching for industrial robots. The programmer is required to physically grab and guide the robot manipulator into poses or desired motions to define the target points or paths to be followed by the robot. The path is then stored as robot program code which can be called and executed during the production phase. The lead-through programming methodology involves the robot to run in a safe/ Teach mode, where the human operator could safely interact with the robot, by physically touching and guiding it without risk of physical injury to the person. In this mode, the robot will dynamically or passively compensate for the weight of its links and EOAT. [11], [13]

The intuitiveness of Lead-through programming makes it particularly suitable option for certain industrial applications, i.e., arc welding, sealant application, glue dispensing and spray painting. These are operations where the robot tool is required to be moved along a smooth, continuous path as explained in [13]. See Figure 2. However, guiding the robot tool in the work space, through the desired continuous path, while avoiding collisions with the elements of the workspace is a difficult and time consuming task. This is particularly true, when the object to be worked on has a complex geometry or if the path to be followed by the robot is complex in itself.

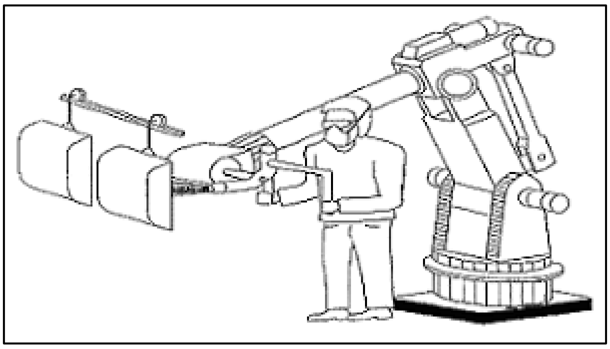


Figure 2 *Pictorial representation of a Lead-through programming process [14]*

The generated program is to be extensively tested, to weed out performance anomalies and possible breach in safety. This is coupled with the downtime of the system and the quality of the program is highly dependent on the skill of the operator, as evidenced by [12].

The utilization of a particular programming style is very much dependant on the particular use case scenario. If intuitive programming is required, then Lead-through method is the way to go, if your task is algorithm oriented and if familiarity is preferred, the Teach Pendant is utilized. However, contrary to all the points which highlight the deterrents of these online programming tools. It is still the most preferred method of programming robots, as 90% of the robots in use today are programmed this way [15].The reason for the prevalence of online programming techniques can be attributed to the fact, that it is familiar to programmers, as all industrial robots come along with a Teach Pendant. Additionally, it does not require an abstract modelling of the environment or computer based simulation/ processing.

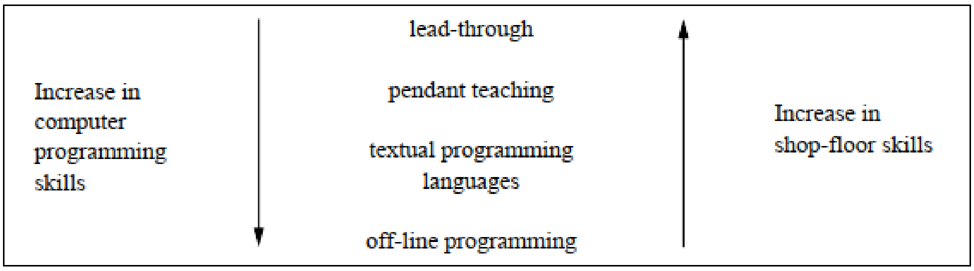


Figure 3 *Shop floor skill VS computer programming*

However, if advanced control algorithms are to be implemented in the production unit and its performance, efficiency, safety, robustness and error response have to be safely tested before downloading them into the real robot controller, Offline programming must be the method of choice for the programmer and the organization. The most significant benefit of using this programming method, as opposed to traditional online programming, is the reduced downtime. The downtime only consists of the duration required for downloading the new program and testing it, instead of teaching and testing it. This makes it a particularly useful method for SMEs and other FMSs, where the robots are prone to be re-programmed more often than in large scale-mass producing environments, and was supported by [16]. Despite its popularity, only a minimal percentage of companies are utilizing this method of programming. Developers are looking to reduce the lead time incurred for offline programming by attempting to make the interface more intuitive and easily accessible. The next subsection focuses more on the fundamental working and different techniques on offline programming.

2.1.2 Offline programming

Offline programming is a term which describes the procedure for remotely programming industrial robot manipulators through a graphical user interface, which provides the user/ programmer, the means to model and simulate the required operations of the robot and its working environment. The user has to set up the robot model and the environment in which the robot operates and then define the interaction points of the robot within the environment. The inverse kinematics details for the robot manipulator can be obtained by using the homogenous transformation matrices and the corresponding Denavit-Hartenberg parameters for the specific robot model. The process requirements of the robot at these individual process points and their corresponding kinematics data is essential for the generation of the code which is understandable by the robot controller. Offline programming methods significantly reduce the downtime of the robot in production lines, cutting down on stoppage expenses and the robot code can be very easily input to the robot. [17]

The security and efficiency aspects of utilizing these offline programming software make it a desirable option. The communication can be established between the PC containing the offline programming tool and the robot controller by means of standard communication protocols (Ethernet, RS 232, etc.). Modifications to the robot program can be done directly on the PC, thus eliminating the requirement of the Teach Pendant to be connected to the robot, preventing security breaches and program alteration by unauthorized sources, as shown in [18]. The efficiency and the ease of utilization aspects of the offline programming tools are constantly being improved by the developers and with computers becoming more powerful and graphically advanced, several approaches were adopted in creating offline programs. They include:

- Icon-Based Programming (see [19])
- Data Flow Diagrams (see [20], [21])
- CAD-Based Programming (see [22])
- Wizards Based Programming (see [24])

The CAD-based programming and Wizards based programming will be the approaches discussed briefly in this subsection.

The CAD-based programming methodology is the most traditional and widespread style of offline programming in industrial robots. The operations and the principle behind this technology was discussed in the initial phase of this subsection. These software tools are constantly being upgraded to improve their usability and reception. Features like automatic path generation, creating targets by just clicking in the virtual space and application oriented features (mainly for the domains of welding, painting, pick and place) enable the users to program the robot operations with minimal programming or robot oriented experience, is documented in [22]. See Figure 4.

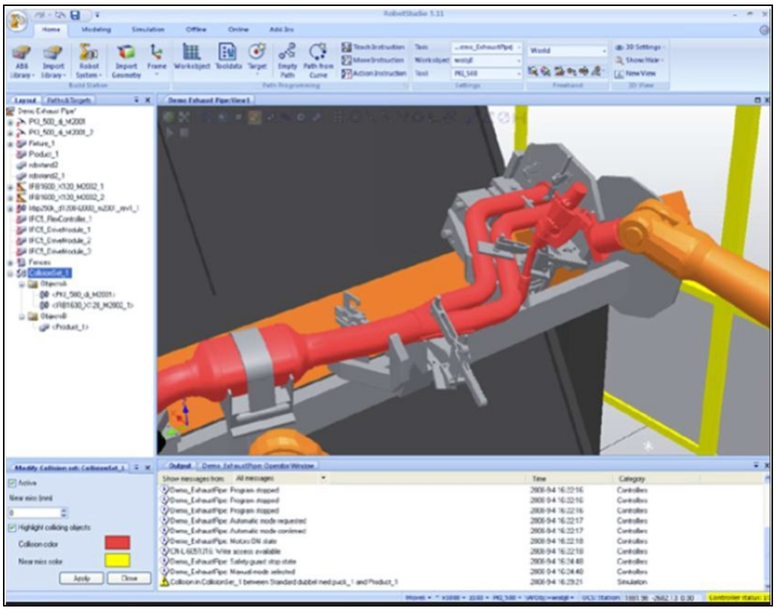


***Figure 4** ABB Arc Welding application- RobotStudio interface [11]*

Wizard-Based Programming is another feature introduced by specific offline programming tool vendors which includes the usage of wizards or options oriented structured guidance. The user is guided with prompts and options, which guides them to create or modify robot programs (paths and logic). Wizards are an up and coming feature in offline programming tools, they are currently being used by Universal Robots [23] in their simulation software tool. Wizards help the user feel more in control of the process, as they ensure that the operator is making educated choices at each step. This speaks volumes for the advancements in the interface of these software tools. With improvements in technology and processing power of computers, the capabilities of these offline programming tools has also been extended.

Current offline programming tools are capable of defining the operations and control of more than one robot manipulator in the same work environment. Interaction between the robots is also possible and can be controlled in the same work session. The advancements in robot controller technology have enabled the usage of a single controller to commonly govern multiple robots in real time, simultaneously. Multiple commands have also been introduced to coordinate the functioning of these robots with respect to one another. The benefits of interacting robot manipulators and the increased productivity of the production lines implementing these multi robot cooperation systems have been documented. Implementing common control over these additional axes has enabled the performance of tasks which would exceed the capability and the level of work intricacy as compared to individual robot manipulators, as highlighted by [24].

The short comings of these single arm robot manipulators were overcome by the introduction of Dual arm robots, which was the culmination of advancing tech and the necessity of individual robots which were capable of diverse, intricate and reliable operation.

2.2 Dual-arm Robots

The earliest robot manipulators were designed to be anthropomorphic, the inspiration for their design was to represent a human being carrying out any particular operation. Infact, some of the very first systems which resembled robotic manipulators were dual-arm. A few examples include the manipulators created by Goertz (as shown in Figure 5) in the late 1940’s for handling radioactive materials, as documented in [25], dual-arm teleoperation devices were fashioned in the late 1950’s for deep-sea exploration (as shown in Figure 6) and further experiments were conducted by NASA’s Johnson Space Center on this technology in 1969, described in [26]. The above mentioned examples give us an ample time reference towards the nascent origins of systems which fairly resembles the robotic manipulators of today.

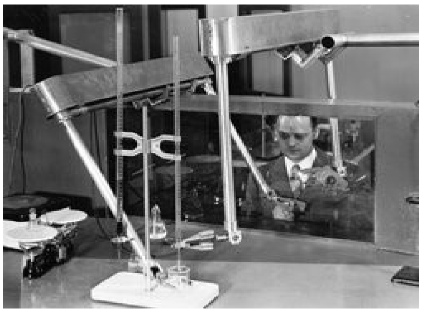


Figure 5 *Goertz's mechanical slave-master manipulator [25]*

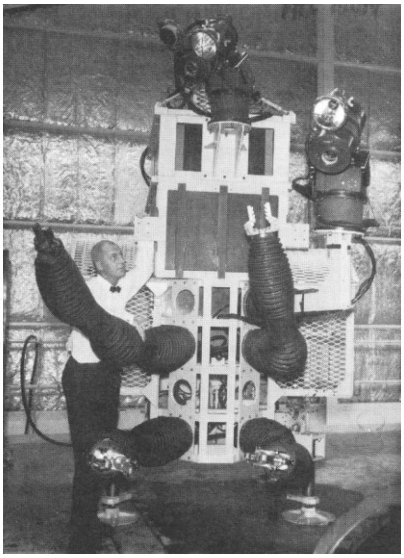


Figure 6 *Hughes underwater mobot [14]*

The current trends in robotics have evolved to such a level, that the manipulators behave more human-like and are intended to be utilised in environments which was originally designed for being operated by actual human beings. However, majority of the anthropomorphic robot manipulators available in the market today are single-arm. These single arm robots have been the norm since the 1980's, when most of the work pertaining to visual servoing was developed, as evidenced by [27].

This portion of the second chapter contains three sub-sections. The first sub-section addresses the scenario of industrial robots as a whole and their relevance in industry 4.0. The next sub-section focuses on the functionality of single-arm robots and the criteria which motivates the utilization of dual-arm robots. The final subsection documents a case study which compares the utilization of single-arm and dual-arm manipulators for an automotive assembly process, and highlights the areas where the dual-arm robots outperforms their single arm competitors.

2.2.1 Industrial robotics in Industry 4.0

A crucial requirement of Industry 4.0 is the implementation of autonomous production concepts, which are being predominantly performed by intelligent robots; emphasising mainly on flexibility, safety, versatility, interoperability and collaboration (wherever required), as supported by [28]. This has resulted in the exponential utilization of industrial robots, in every conceivable domain. Evidenced by the number of industrial multipurpose robots (various manufacturers) operating in Europe, which has doubled in numbers since 2004, as shown in [29].

The industrial revolution has brought about a wide array of changes to manufacturing processes, manufacturing outcomes and the effects they have on business models. This is due to current industrial robots having increased productivity, customizability and flexibility, thereby, improving the speed of production and the quality of the product. All of this while cutting down on operating costs. It is not surprising that the evolution of industrial robots in terms of technology and their increase in numbers is the way it is, it is worth making the investments to develop their technology and utilise them to solve the constantly evolving requirements of modern industries. [28]

2.2.2 Dual-arm over single-arm

The previous portions of this section discuss about the utilization of robotics in the current industrial setting and the predominance of single arm manipulators. According to the International Robotics Forum [30], majority of the robots used in the industry are Cartesian, SCARA, Articulated and cylindrical; these fall under the category of serial link manipulators; Delta robots are also widely in use and they fall under the category of parallel link manipulators. These classifications were based on their mechanical construction and the work envelope covered by their arms/ links (as shown in Figure 7). Single arm manipulators are capable of performing a wide range of operations including welding, materials handling, assembly, machine tending, etc. with high levels of satisfaction.

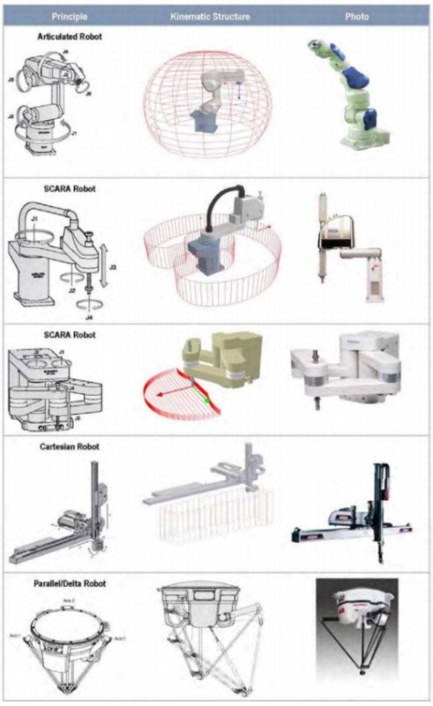


Figure 7 *IFR classification of robots based on mechanical construction [20]*

However, certain applications render the use of single arm robots at a disadvantage. Especially, if the operation required to be performed is either complex material handling or an assembly operation; the usage of traditional single armed industrial robots may require modifications to be made on the existing machinery in the system or specialized/ complex end of arm tooling. Nonetheless, these shortcomings can be overcome by implementing dual armed robots (see Figure 8) for complex manipulation, reducing impact on existing production lines, while simultaneously boosting functionality. [31]

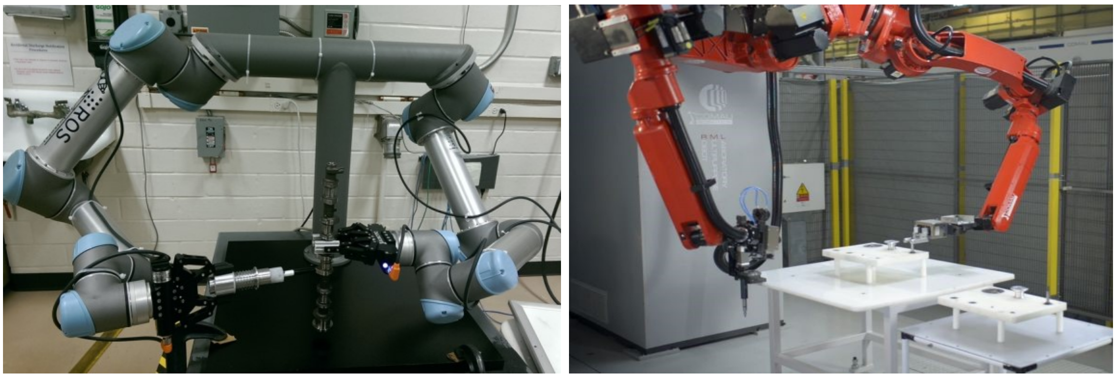


Figure 8 *Dual-arm robots in operation. Universal Robots (left) and COMAU (right)*

The spheres in which dual-arm robots exhibit an advantage over single-arm manipulators are:

- Multitasking- Complex bimanual operations can be performed by independent or synchronous operation of the two arms to perform complex tasks
- Cost effectiveness- Dual-arm robots may replace two single-arm robot system to perform the same task, or reduce the complexity of fixtures and eliminates the need for ancillary subsystems, thereby reducing costs
- Space utilization- The amount of space consumed is lesser than that of an entire single arm manipulator based system. [31]

Other factors (which are independent of each other) which motivate the utilization of dual-arm setups include:

- Similarity to operator- Especially attractive in teleoperation applications, where the bimanual tasks performed by the operator, can be transferred to the dual-armed slave at a remote location (see [32]).
- Stiffness and Flexibility- Dual arm manipulators can combine the strength and stiffness of a parallel manipulator along with the flexibility of a serial link manipulator (see [33]).
- Cognitive Motivation- The human-like physical interactive behaviour and their similarity of operation to a dual-armed manipulator setup, improves the human's cognition and understanding of the operation (see [34]).
- Human Form Factor- With the rising demand for robots to replace workers in environments originally designed for them (workers), it is an advantage for the manipulator to resemble a human-like form [6]. A direct outcome of the above is the consumption of less space, having a lower cost than two single arm units and the reduced task of having to redesign the work space (see [31]).
- Manipulability- A strong motivation for researching and developing efficient means of dual arm manipulation is the ability to position/ control, both the components involved in a particular assembly operation, with respect to each other. A use case for peg-in-hole task, where one arm positions the hole and the other arm slides in the peg, is documented in [6]. A use case for a screwing task, where one arm handles the nut and the other arm screws in the bolt is documented. Domestic tasks such as washing dishes is within the applicability of dual-arm robots as they possess a high degree of task space redundancy, which enables them to perform such tasks at an optimal level of performance, is stated in [35].

2.2.3 Dual-arm manipulation- A case study

A pertinent illustration of the benefits of implementing a dual-arm robot over traditional single-arm manipulators, in an assembling scenario in the automotive industry, is documented below. [36]

The sequence of the assembly operation is to lift and place a vehicle traverse; then lift and place a body computer on the traverse; and then lift the screw driver, perform the screwing process and replacing the screw driver. The criteria for comparison would be the EOAT utilized, the workspace required, the complexity of the process and cost. [37]

The COMAU smart dual arm robot is the bimanual manipulator of choice, used in this implementation. The **Figure 9** shows the simulated work environment for the dual-arm manipulator, the Figure 10 shows the tooling for each arm, and the Figure 11 shows the work envelope of the dual-arm robot. [37]

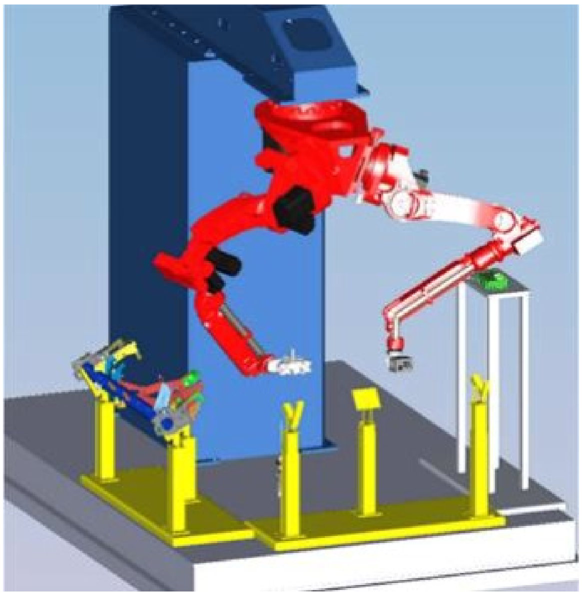


Figure 9 The work environment and dual-arm robot [37]

Figure 10 *EOATs used in the setup [left arm and right arm] [37]*

The work envelope of the dual-arm robot is depicted in the Figure 11, as it performs the assembly operation across the work environment,

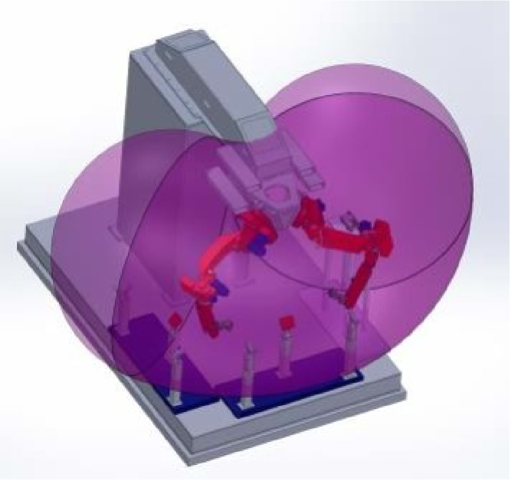


Figure 11 *Work envelope of the dual-arm robot [37]*

The usage of two EOATs are justified for performing the pick and place operations of these automotive components. As this illustration is just to showcase a comparison, I am not delving much into the nature of the objects to be handled and assembled. The Figure 12 depicts the work envelope of two single arm manipulators working together to perform the same assembly operation, with the same EOATs. The Figure 13 showcases the operation being performed by one single arm manipulator, but with complex EOAT. [37]

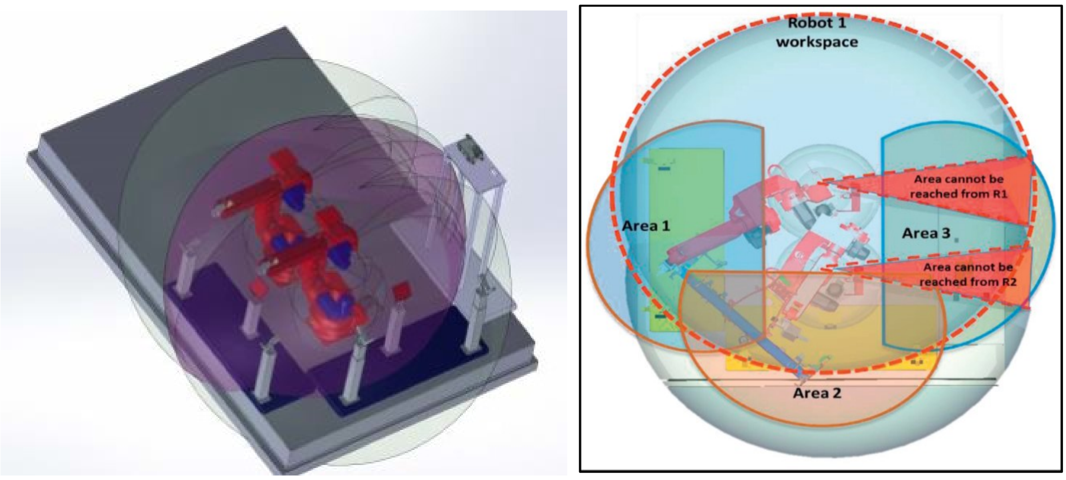


Figure 12 *Work envelope of the two single arm robots (left); interferences and unreachability (right) [37]*

In the case of the utilization of the smart dual arm robot as seen in Figure 11, there is a better exploitation of the workspace, the reachability of the robot is much higher and can be extended as the robot can also be rotated on its external rotary axis (joint base of the two arms), and the programming and coordination of the arms is easier.

In the case of utilizing two single arm manipulators, the workspace of the robots intersect, as shown in Figure 12 (left), each other and are more restricted as compared to the dual arm robot. The limited reachability of the robots while carrying the vehicle traverse is shown in Figure 12 (right); the assembly operation takes place in the area 1-3, the study conducted shows that the area 1 is reachable by both the robots, whereas robot 1 cannot reach area 2; the robots will collide when the vehicle traverse is moved from area 1 – 2; additionally both the robots have limited reachability in area 3, eliminating the possibility of assembling the body computer. The programming of these two individual robots to work together is more complex and expensive as it requires a multi-robot controller along with the cost of an additional manipulator.

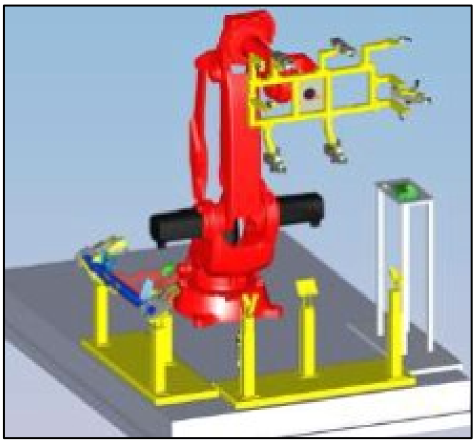


Figure 13 *Single arm robot with complex gripper [37]*

In the case of utilizing a single-arm manipulator with a product specific and complex tooling (as shown in figure 8) for lifting the vehicle traverse, the weight and complexity of the gripper would be deterrents, and cannot be utilized to grasp any other component as opposed to the standard grippers utilized (shown in figures 5a and 5b). The cost of the gripper is increased; the payload to be handled by a single arm is increased, thereby, warranting a bigger and more expensive robot manipulator, and an ATC would also be required for handling the body computer.

Compared to all the combinations of utilizing a single-arm manipulator, the dual arm manipulator is a superior option to perform tasks in an assembly line, as it is suitable for multitasking and is cost efficient. Cost efficiency is determined by its ability to replace conventional robots, expensive fixtures and ancillary sub-systems [37]. This leads us to another important aspect to consider while employing a robot based solution. Implementing the right tooling for the right job is a critical requirement for any manufacturing or material-handling process. The next section of the chapter discusses about the implementation of end effectors in robots, with an emphasis on material handling.

2.3 Grippers and Grasping Technologies

The process of handling products in an industrial setting is often underrated and is viewed as simple or technically trivial. From the production point of view, material handling does not add any value to the product and is considered secondary to the manufacturing process. Often, the gripper selection is considered as the last requirement to be met, while creating an automation process, resulting in it being a compromise solution rather than the exact required solution. Otherwise, only the most common grippers are utilized to perform the task, all of which was documented in [38]. If done incorrectly or inefficiently, it increases the cost of production, thereby increasing the final cost of the product and reducing profit margins. Therefore, significant emphasis must be placed on employing proper technology and practices to ensure that the handling of the product is as efficient as possible.

Identifying and selecting the best gripping solution for the application can be a daunting task for any applications engineer, as there are so many options available (in terms of technology) with their own pros and cons with literally thousands of different combinations, part identification numbers and gripper name variations for each technology. For this implementation however, only the EOAT for material handling is researched and discussed. This narrows the discussion down to relevant concepts, as the options available for gripper selection are vast. The grippers documented here are classified based on the nature of their operation, they are:

- Mechanical grippers (fingered)
- Vacuum grippers (suction)
- Magnetic grippers (Magnetic Switchable Devices)

2.3.1 Mechanical Grippers

Majority of the mechanical grippers or fingered grippers are a variation of three fundamental designs:

1. Parallel grippers (2 fingered)
2. Concentric grippers (3 or more fingers)

3. Angular grippers

Parallel grippers are essentially two fingers opening or closing, by sliding parallel to the work-piece. The gripping action is done by the two fingers closing in on the outside surface of the work-piece or opening out and applying enough pressure to grasp its (work-piece) inner walls. The nature of grasping is dependent on the geometry and other characteristics of the work-piece i.e. weight, dimensions, material, holes, provision for grasping, etc. A commercial two fingered gripper is shown in Figure 14.

Two jaw parallel grippers are the most commonly used mechanical grippers commercially, as it is extremely versatile and can handle a wide array of part shapes and sizes

Figure 14 *Two jaw parallel gripper [39]*

Concentric fingers are utilized to center the work piece along the gripper axis, between the fingers which are offset radially, at equal angles. Three-finger grippers have fingers which are offset by 120°; the fingers slide to a close uniformly and aligns the work-piece along the tool axis while it is being gripped. A three-fingered gripper is shown in Figure 15. Concentric grippers offer a higher degree of grasping, compared to their two fingered counterparts, this is especially useful if the object to be handled has to be handled at high speeds.

Figure 15 *Three-fingered gripper [39]*

Angled grippers approach the work-piece at the sides from various angles i.e. 30°, 40°, 80°, etc. They are utilized for grasping larger and odd shaped work-pieces and in applications where space is too constricted. An Angled gripper is shown in Figure 16.

Figure 16 *Angular two finger gripper [39]*

When mechanically grasping the work-piece at particular points may damage the part being handled (deformation, surface finish, etc.), there are other medium of gripping which can be utilized. The next subsection focuses on another widespread method of material handling.

2.3.2 Vacuum Grippers

Vacuum grippers or suction cup grippers are a highly effective gripping solution for automated material handling industries, because of its simplicity and applicability for a wide range of requirements. A vacuum gripper typically contains a suction cup (or an array of suction cups) which essentially come into contact with the work-piece to be handled. The vacuum cups are usually made of rubber or polyurethane, and are connected by pneumatic hosing to a device which generates vacuum. These devices may include vacuum pumps, suction bellows, ejectors, etc. [40]. The vacuum is generated when the suction cups fully covers the surface to be gripped (no air leak condition/ fully sealed) and the air inside the line is sucked out. This results in the gripping of the object

Vacuum grippers have an application range of -50°C to 200°C and are efficient at handling smooth surfaces (uniform surfaces with minimal surface roughness). They find their applications in packaging industries; part feeding systems in automotive industries; handling material which have a high surface-area to weight ratio, i.e., sheet metals, glass sheets, cardboard, etc. Multiple suction cups can arranged serially or in arrays, especially while handling larger material, as shown in Figure 17. [40]

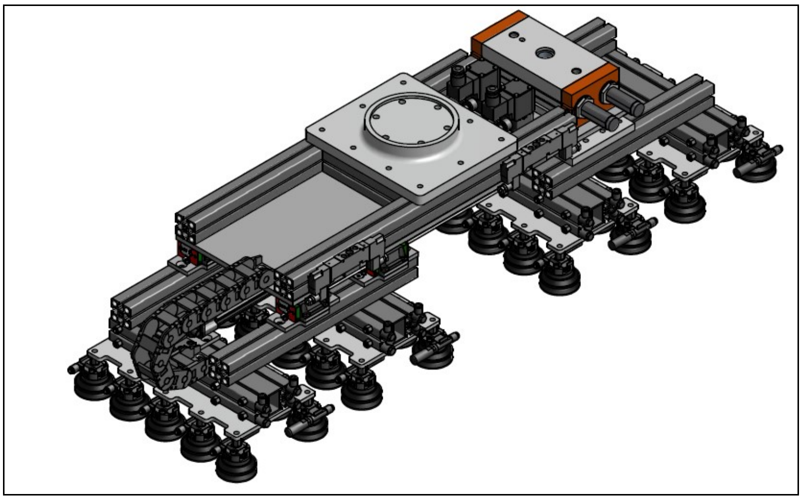


Figure 17 *Vacuum gripper array [40]*

However, there are some downsides to utilizing vacuum grippers. Even though the advantages and benefits of using vacuum grippers to automate material handling operations outweigh the cons. If the designing and the execution of the implementation is done incorrectly it could result in significant problems. Some of them are:

- Repeated handling of a part by vacuum grippers may alter the position/ orientation of the part. Special provisions must be made to ensure that the orientation of the part is retained while being gripped, handled and released.
- Parts having curvy or sharply angled surfaces, porous or corrugated surfaces, oily surfaces, and dirty surfaces may have incomplete grasping results, because of the inefficient generation of suction.
- The suction cups may leave impressions and markings on the surface of the parts being handled. These are especially evident when the material handled is glass, sheet metal or other similar material. [40]

2.3.3 Magnetic Grippers

Grippers which utilize permanent magnets to create the gripping action by turning the magnetic field ‘on’ and ‘off’ are Magnetic Switchable Devices (MSD), as documented by [41]. They are currently gaining a lot of attention, especially when it comes to automating the handling of ferrous material, of various dimensions and masses.

The working principle behind how two permanent magnets inside the gripper housing can be turned ‘on’ and ‘off’ is depicted in Figure 18. The gripper consists of two diametrically magnetized disc magnets, stacked on top of one another, with one fixed to the housing and the other capable of rotating along the common axis to a fixed degree. When the movable magnet is turned in such a way that the opposite poles of both the magnets are in the same direction (Figure 18, left.), the magnetic flux lines (which are a representation of the magnetic field) negate each other and the magnet field is just running through a closed circuit inside the housing and the gripper is considered to be in the ‘off’ state. When the movable magnet is rotated to such a degree that both the poles of the magnet are aligned (Figure 18, right.), the two magnetic blocks behave like an individual magnet and their combined flux lines flow through the side walls of the housing, and on to the steel plate or work-piece. This is the ‘on’ state and the work-piece is gripped by the principle of magnetic attraction. [42]

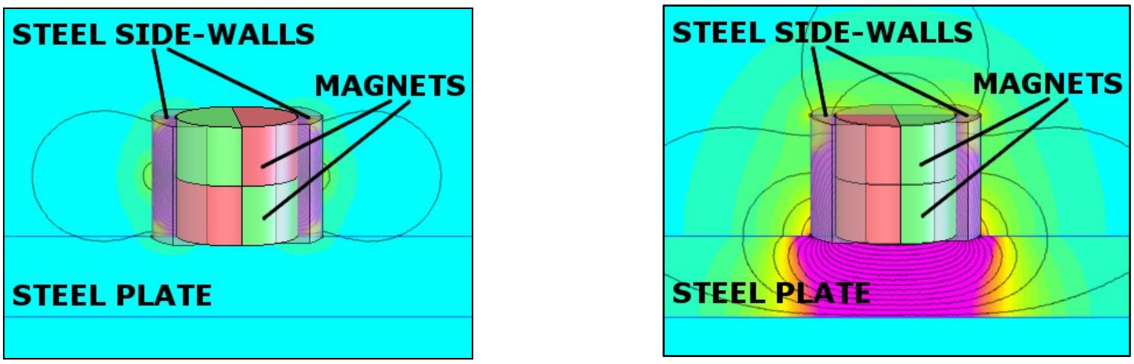


***Figure 18** MSD with Magnetic poles negating each other [Off state] (left); and Magnetic flux flowing into the steel plate [On state] (right) [42]*

The magnets do not come into direct contact with the material being handled, the magnetic field is focused out, through pole shoes. The pole shoes are designed to accommodate the profile of the part being gripped. As shown in Figure 19. The simulation for the magnetic flux intensity is also depicted in Figure 19. The pole shoes are ferrous and must be resistant to wear, as it comes into more frequent contact with the part to be handled. [40]

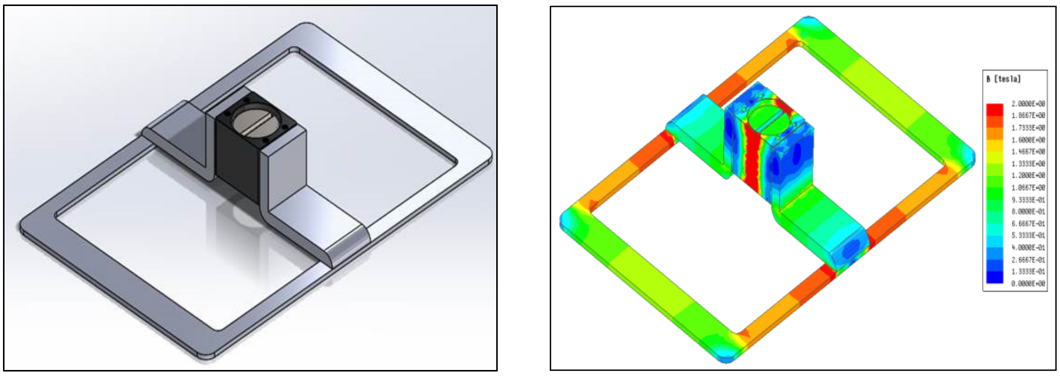


Figure 19 *Commercial magnet with customized pole shoe (left); Magnetic flux distribution over the sheet metal profile (right)*

Magnetic grippers offer unique capabilities and significant advantages over the more traditional alternatives used in EOATs for material handling. They are compact and light weight and are a reliable replacement for vacuum grippers and traditional finger grippers.

There are a few disadvantages to using MSDs, some them are:

- Only ferrous material can be handled, limiting applicability
- Residual magnetism is a concern, especially in cheaper gripper variants with improper pole shoe and housing design
- De-stacking thin material. However, MSD solutions with shallow field technology are available to handle thin stacks of sheet metal.

2.3.4 Anthropomorphic Grippers

The growing interests in gripping technology with modern servomotors and the availability of smarter control methods, and materials have enabled the advent of anthropomorphic grippers, which are essentially end effectors which resemble the appearance and functionality of the human hand. The vast majority of currently available EOATs are intended for specific definite purposes and the performance of complex operations requires complex tooling design which is dextrous but does not have anthropomorphism, as documented in [43]. There are numerous cases where robotic end effectors are anthropomorphic but have poor dexterity. However, there are incentives for adopting the human hand design with high levels of dexterity, especially in environments which are tele-operated by man, prosthesis and rehabilitation, etc., as shown in [44]. The uniqueness of the human hand brought about by the millions of years of evolution enables it to handle a large variety of objects and have an infinite range of movements, thus anthropomorphism in robot EOAT with corresponding levels of dexterity enables the robot to interact more effectively with the environment, as determined by [45]

The grasping potential of the anthropomorphic grippers for handling components of various shapes, sizes, weights, consistency, colours, temperatures, etc. are conceptualised and compared with the grasps made by trained machinists. The Figure 20 has a comparison between the object characteristics and the grasping characteristics of the EOAT. [46].

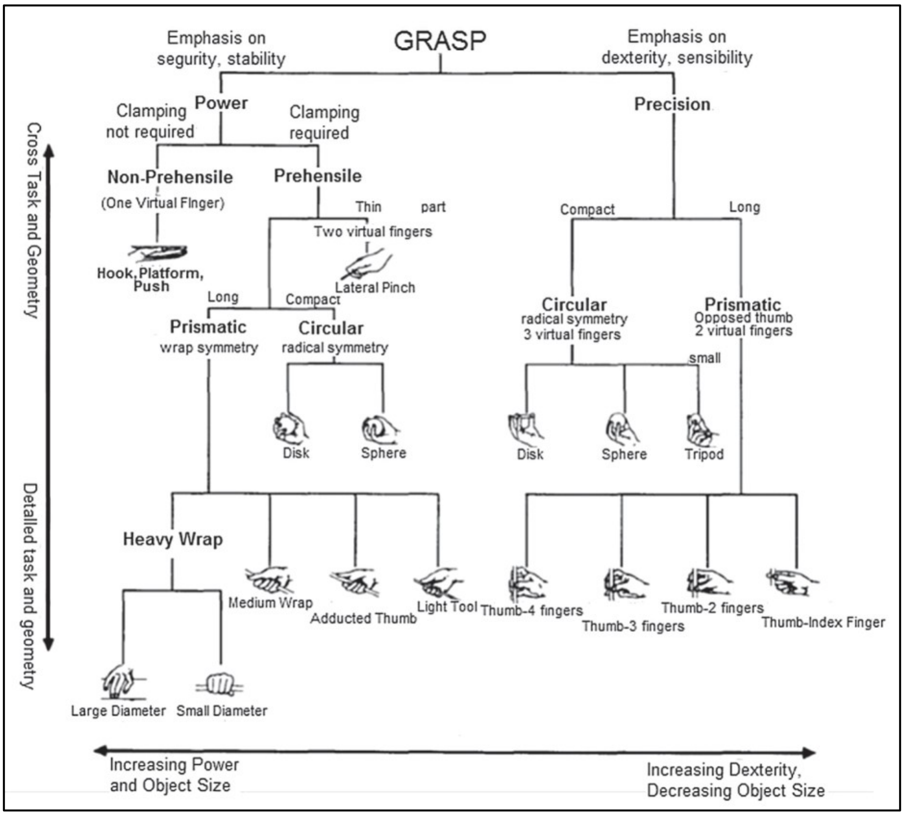


Figure 20 *Classification of Grasping Techniques [46]*

The anthropomorphic grippers have a higher degree of dexterity, a larger domain of applicability and possible micro-movements of the grasped object; all of which when compared to traditional mechanical grippers. The downsides for implementing this solution would include the complex integration of the hand to the manipulator, complexity in programming the grasping operations, the cost of the manipulator as opposed to standard gripping options. The implementation the anthropomorphic gripper works best when the object characteristics and the corresponding grasping dynamics are constantly changing. The Figure 21 showcases an AR10 gripper which is a commercially available anthropomorphic gripper with 10 DOF [47].

Figure 21 *Commercial Anthropomorphic gripper [47]*

2.4 FASTory

The FASTory assembly line is located in FASTLab, at the Tampere University- Hervanta campus. See Figure 22. It is currently a representation of a discrete manufacturing system, and was refurnished and retrofitted from its original state, where it was employed in the assembly of mobile phone components in Nokia.

Figure 22 *Current FASTory layout*

The functionalities of the FASTory was very briefly introduced in the problem statement section of the Introduction chapter. This section sheds more light on the construction and the capabilities of this intelligent production line. The assembly line consists of 12 cells or workstations (WS) which are physically arranged in a loop topology as can be seen from its web based simulator in Figure 23. This essentially means that a pallet, which holds the canvas for the drawings of the mobile phone components, are introduced into the line and removed from it at the same place (WS7); and the loop topology ensures that the pallets are capable of physically being transferred to all the workstations, via conveyors and can stay in the line indefinitely (as per production requirement).

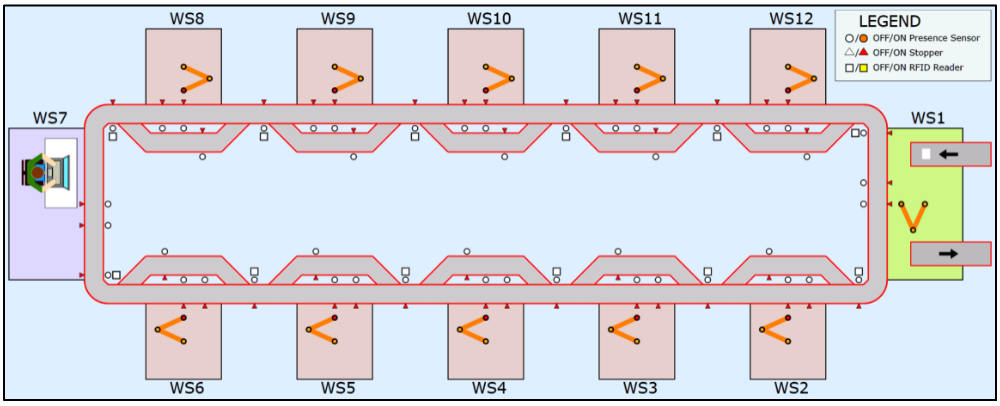


***Figure 23** FASTory Simulator- Loop topology layout depiction [8]*

The main cell (WS1) is responsible for loading the empty paper (raw material) and unloading the drawn component (completed product). The buffer cell (WS7) is used to load and unload the pallets and is called a buffer because it can store up to 18 pallets. The buffer cell acts as an Automatic storage and retrieval system (AS/RS). The remaining cells (WS2, 3, 4, 5, 6, 8, 9, 10, 11 and 12) are identical in their function, and are used to represent the production process, and can be called production cells or basic cells. Wherein, they can draw three different variants of frames, screens and keyboards, in three different colors (red, green and blue), respectively, in any required combination. The components drawn can be seen in the Figure 24. This results in the possibility of 729 ([3 frames x 3colors] x [3 screens x 3 colors] x [3 keypads x 3 colors]) variants of the final product.

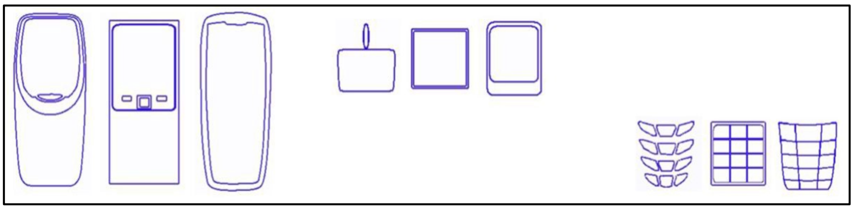


***Figure 24** Mobile Phone components [8]*

The individual workstations were all originally installed with individual SONY SCARA robots (except WS7). These robots are responsible for loading and unloading the paper in the WS1 and performing the drawing operations in the remaining Workstations. The WS7 is implemented with a servo controlled arm with 4DOF, for loading and unloading the pallets. The individual 3D models of the three types of cells are shown in Figure 25, Figure 26 and Figure 27. However the manipulators in the cell are being upgraded and the functionalities of the FASTory line are being extended. More details regarding this would be provided in the later chapters.

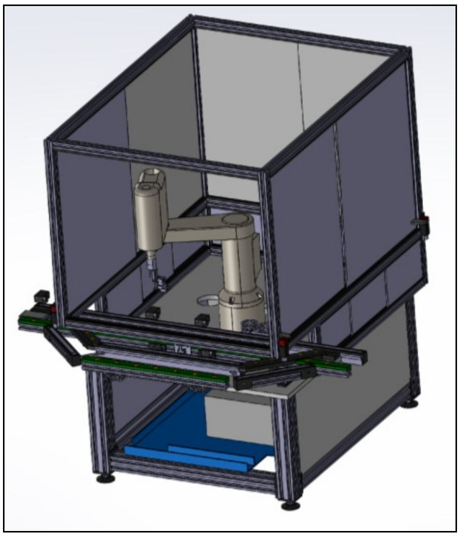


Figure 25 *Basic Production Cell*

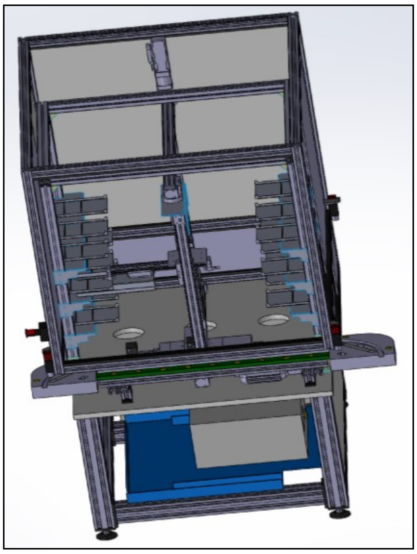


Figure 26 *Buffer Cell- WS7*

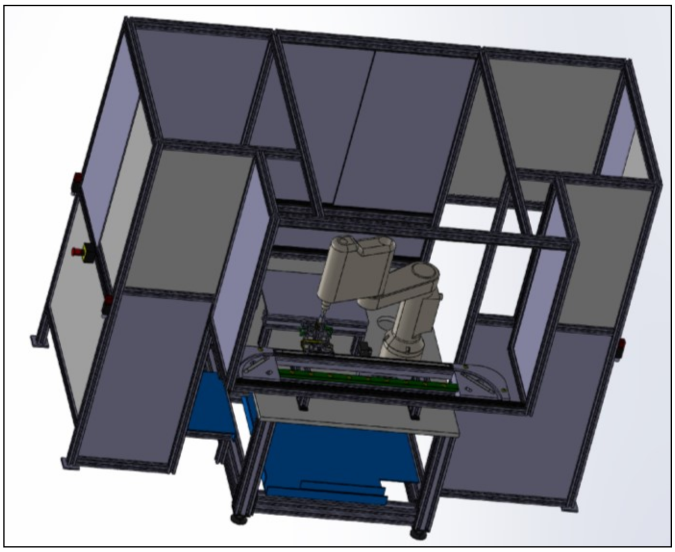


Figure 27 *Main Cell- WS1*

The Workstations are physically connected to each other by means of conveyors, in the loop topology as shown in Figure 23. It can be noted that all Workstations except WS1 and WS7 have a main conveyor and a bypass conveyor. WS1 and WS7 are just fitted with the main conveyor. The main conveyor is the one where the manipulators in the cells perform their operation, be it loading/ unloading the paper and/or pallet or drawing the components. The bypass conveyor is used to skip a particular workstation which is currently responsible (or set to perform) for performing a particular drawing operation, on the paper fitted to the pallets; this ensures that the loop topology does not bring the smooth flowing production process to a halt, by stalling the flow of the pallets.

The conveyors are split into zones, and each zone serves a particular purpose. The graphical representation of the zones from the online FASTory simulator is shown in Figure 28. The physical counterpart has the same setup and each zone is fitted with a proximity sensor to detect the presence of a pallet. RFID readers are located in each zone and zone 5, in all of the workstations. These read the NFC tags which are fitted on to each pallet and are used to monitor the position of the pallets in real time.

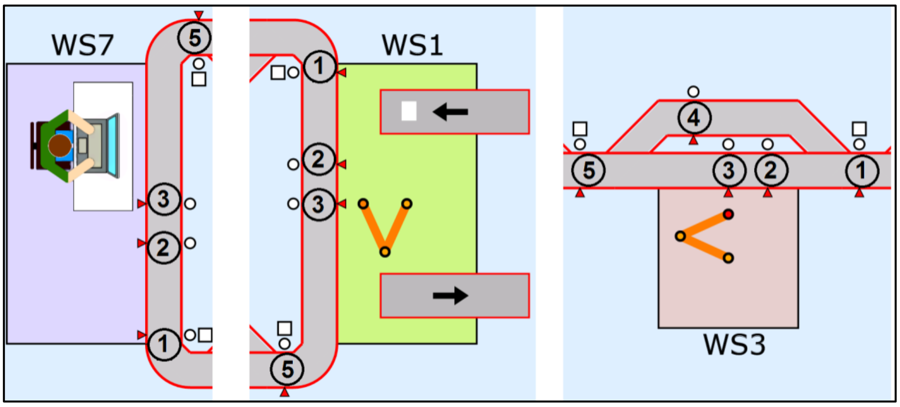


Figure 28 *Conveyor zones in FASTory [8]*

The utilization of these zones and their relevance in each of the workstations are listed below:

- Z1- These zones are at the entrance of all the workstations. It reads the ID of the pallet being transferred from the previous workstation. This zone is used to document the location of the pallet (current WS). The decision to allow the pallet to enter the workstation or to move it to the next station, through the bypass conveyor, is made in this zone. After the orchestrator is made aware of the location of the current pallet location.
- Z2- This zone acts as a buffer inside the workstation. If the zone 3 of the particular workstation is occupied, the additional pallet can be queued in the same workstation. This zone is present in all the workstations of the FASTory
- Z3- This zone is the production zone. The intended operation of the manipulator in the cell is performed on the pallet present in that zone. This operation may be loading/ unloading or drawing. This zone is also present in all the workstations.
- Z4- This zone is present in the bypass conveyor. The pallet being bypassed on to the next workstation passes through this zone. The pallet maybe halted at this location or passed on without halting, based on the existing scenario in the line. The two functionalities of this zone are, deciding whether the pallet from zone 3 to be moved to zone 5 or whether the pallet from zone 4 to be moved onto zone 5. Depending on the priority or condition determined by the orchestrator. This zone is present in all the workstations, except WS1 and WS7.
- Z5- This is the exit zone, which the pallet passes through when it leaves the workstation. This zone is also available in all the workstations of FASTory.

With this architectural layout, the individual workstations with their robot manipulator and the conveyor is represented as a Remote Terminal Unit (RTU), making a total of 12 RTUs (12 robots and 12 conveyors). The physical features and capabilities of the FASTory line, pertaining to its layout, the nature of production, individual Workstation functionalities and product diversity has been documented so far. The control of the FASTory line and the orchestration of the individual RTUs are explained in the next subsection.

2.4.1 System Control Architecture- FASTory line

The individual RTUs of the FASTory line are all controlled Individual INICO S1000, which is a web based industrial controller [48]. The INICOs natively implement the Device Profile for Web Services (DPWS) stack, which enables the utilization of web services to discover and invoke, resource-constrained devices.The S1000s are programmed by structured Text (ST) language, and are highly versatile. It can be interfaced with sensors and actuators through I/Os and also has optional additions which enable it to connect to other peripheral devices through the RS232 serial port, analog inputs and through Modbus/TCP. They can communicate with other S1000 devices and other high level applications through Web Services messaging, in the SOAP/XML standard format [49], [50].

The sensors and actuators are all separately grouped as well defines functional units, their functionality is encapsulated and is made available to the system as web services. This enables these groups to be independent of the other components and follow a distributed approach, wherein they can interact amongst themselves. The versatility of the S1000s and their inter-communication capabilities amongst other INICOs enable the elimination of hierarchies as all of the equipment in the RTUs can be accessed directly by the orchestrator and the MES through the use of web services, as explained by [51]. The system architecture of the FASTory line is depicted in Figure 29.

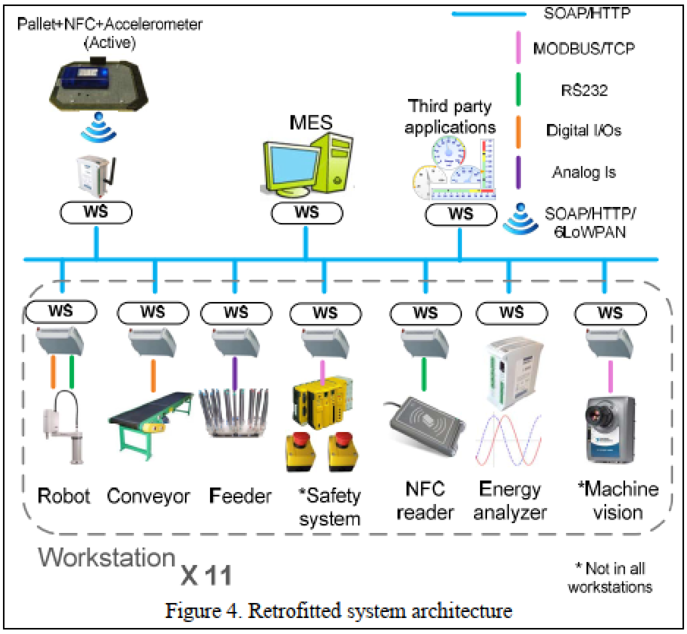


***Figure 29** System Communication Architecture [51]*

This system architecture varies from RTU to RTU but they have the same principle. This section of the State of the Art chapter has provided insights about the FASTory environment, where the implementation of this thesis work is going to take place. The next section will focus on the learning value from the research conducted for identifying the State of the art practices and technologies, and, how that is going to aid in the completion of this thesis work.

2.5 Summary

This section of the chapter focuses on making a correlation amongst all the previously discussed sections in this chapter. It aims to make sense of all the information presented, which is relevant towards the completion of this thesis. The first aspect to be considered is the functionalities and the capabilities of the modified work environment. The environment and all its elements were created using the 3D modelling software ‘Solidworks 2017’ [52], and the offline programming tool for Yaskawa motorman robots ‘MotoSim EG VRC 2018 SP2’ was the software of choice used to program the robot operations and simulate the elements of the Workstation [53].

The reason MotoSim was the offline programming tool of choice was because, the dual arm manipulator Yaskawa SDA10F was the industrial robot of choice [9]. The utilization of a dual armed robot replaces a SCARA robot and a 4DOF manipulator AS/RS system.

It also has the additional capability to interact directly with a mobile robot. It also replaced the excessive conveyor system in the existing main cell for paper transfer. The utilization of the dual armed robot has provided opportunities to implement a wide array of tooling.

The parallel grippers are considered to perform the handling operations, the vacuum and magnetic grippers were also considered, but they were later discounted due to factors such as simplicity of implementation and cost factors, respectively, for this particular operation. The advantage of utilizing a dual armed robot enabled the utilization of two simple finger-like structures on each hand to perform the heaviest material handling operation, utilizing its bimanual operation capability which makes the system behave in a human-like manner. An existing EOAT system with two sets of pneumatic clamping devices are also used. These tools are fitted to a holder in a modular manner, enabling the fitting of four individual EOATs to the two arms of the robot. All of the implementation is done on the FASTory line which would be undergoing a physical refurnishing to be able to accommodate all the required changes.

The buffer cell and the main cell are going to be merged in functionalities and capabilities and the orchestrator of the physical operations and the interactions in the line would be the dual-arm manipulator. The robot manipulator and all the associated sensors in the workstation and in the robot tooling are interfaced directly to the MES through the Inico S1000s.

The study of the existing technologies and literature has given me a fresh perspective of actual possibilities and alternatives which can be implemented, and it has provided me the options, allowing me to make a better informed choice when it comes to implementing this solution.

3. METHODOLOGY AND DESIGN PHASE

This chapter of the thesis delves in deeper into the process and the steps considered to implement my solution, based on all the information gained from the previous chapter. The additions to the scope and functionality of the FASTory line and the necessary changes to be implemented, in order to realize the additional requirements would be discussed further in this chapter.

The changes made to the designs of the existing cells, the modifications required for the existing tooling, the creation of the modified environment in the MotoSim Environment and evaluation of the created designs would be discussed in this chapter.

3.1 FASTory line Extended Scope

The FASTory line is a representation of a flexible assembly process, wherein the requirements of the line are production of mobile phones. The production manager/ operator/ actor gives the description and the production quantities of the models of the mobile phones to be drawn. The MES (with existing real-time production data) updates the knowledge base with the new input production data which in turn creates the logic and operation plans for the line and updates the orchestrator which choreographs the actions of the functional units present in all the RTUs to perform the production process. After the model of the phone is drawn the main station removes the paper from the pallet and stores it in the station. This was a high level overview about working of the FASTory and its original scope.

The scope of the FASTory line is being amended and upgraded, and is an additional motivation for ideating this thesis work. The Figure 30 (A) is the original layout which shows the various isolated systems as blocks in the lab. The goal is to interconnect these existing elements to extend their individual operation capabilities.

The upgraded layout of the FASTory is depicted in Figure 30 (B) and currently the operations of the Human-Robot collaborative workstation with the ABB YuMi, the corresponding dual robot cell with the ABB IRB-140 manipulators and the autonomous mobile industrial robot (MiR 100) is integrated with the process operations of the FASTory line. The layout shows additional blocks in the main FASTory block, namely, the material handling cell and the storage buffer cell. These cells are cumulatively the dual arm robot station, where most of the aspects of this thesis implementation are focussed on.

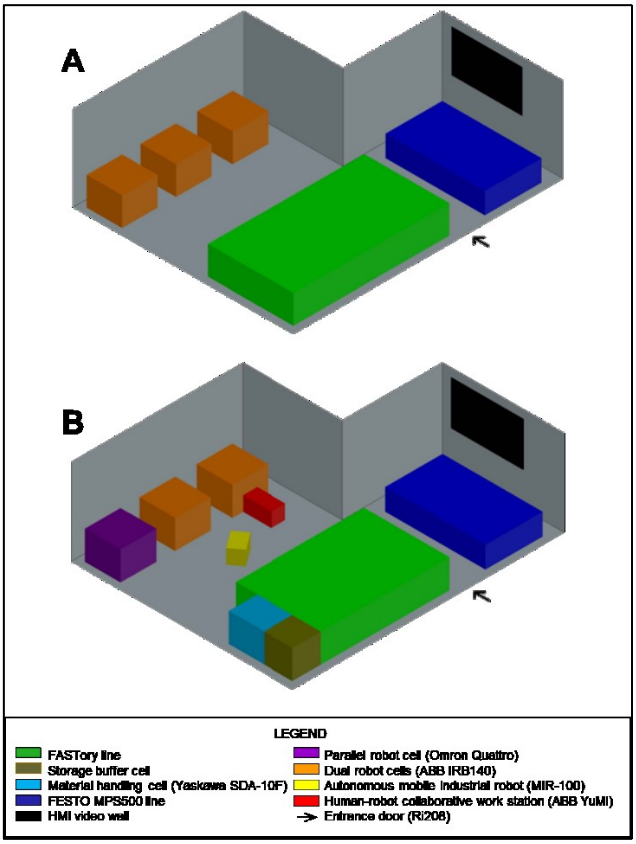


Figure 30 *Original FASTory layout (A); Modified layout (B)*

The change in layout is to enable the following additional processes:

1. The main cell and the buffer cell are merged to form the dual arm robot station.
2. The canvas papers with the drawn models can be removed from the pallets and stored in the baskets, present in the cell.
3. Fresh paper is fed by means of automatic paper feeding mechanism, the dual-arm robot is responsible for positioning the canvas paper onto the pallet.
4. The dual robot also performs the loading and unloading of the pallets similar to AS/RS application of the buffer station.
5. The robot loads the paper filled basket onto the autonomous mobile industrial robot, after the production quantity is met; additionally it can transfer the empty basket from the mobile robot into its designated position in the cell, for loading it with drawn mobile phones.
6. The autonomous mobile industrial robot is used to transfer the paper filled basket to the Human-robot collaborative station from the dual-arm robot station; and it transfers the empty basket from the Human-robot collaborative station to the dual-arm robot station.

7. The Human-robot collaborative station has the individual components of the mobile phone box, which is transferred to the dual robot station by the cobot (COllaborative roBOT) YuMi, by placing it on the input conveyor.
8. The ABB IRB-140 robot in the dual robot station reads the numbering on the individual components of the box structure, arranges it in the require target sequence for the YuMi to assemble, and sends it back out through the conveyor.
9. The assembly operation of the boxes for the individual mobile phone drawings are assembled with the help of the YuMi.
10. The assembled boxes (with the mobile phone drawing inside) are transferred to the Dual robot station by a conveyor.

This is the extension of the production operation capabilities of the FASTory line. The first five bullet points are the operations which fall under the scope of this thesis implementation. The remainder of the operations are performed in the thesis work of R. Bejarano.

3.2 Environmental Modifications

To implement the requirements of the thesis work and to enable the upgradation of the FASTory's process operation the several changes were required to be made to the main cell (WS1). However, the design modifications to the main cell (as shown in Figure 27) was performed on the basic production cell model (as shown in Figure 31), as the main cell 3D model had many elements which were irrelevant and outdated. This would have led to an unnecessary extension in the design lead time. This coupled with issues relating to file type incompatibility were the reason a simpler template (basic production cell) was used.

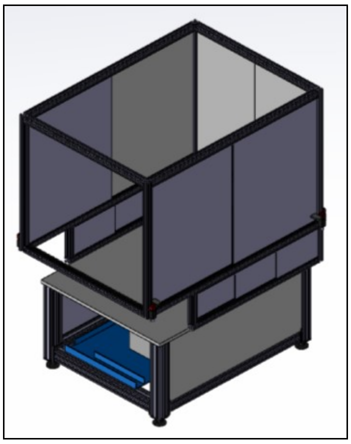


Figure 31 *Basic Production Cell*

The original models of all the FASTory cells were created using the CATIA 3D software for which FASTLab no longer has an active license. The 3D modelling software currently in use is SolidWorks. The compatibility issue was mainly because the 3D model of the basic cell was initially in the '.CATProduct' and it was an assembly file made of elements in the '.CATPart' file format. If the assembly from the CATIA environment was the imported into SolidWorks, the assembly behaves like a solitary block and none of the individual elements of the assembly could be modified individually by utilizing the modelling feature and tools available in SolidWorks.

Therefore the individual parts (.CATPart) of the basic cell were imported into the SolidWorks environments singly, and were saved as .SLDPRT files (SolidWorks compatible filetypes). This provided the feature to use some of the 3D modelling features of the software, i.e. Extrude, Extrude cut, Revolve, chamfers, fillets, etc. Albeit, the 2D elements of the model could not be edited because the imported elements still behaved like blocks, this was sufficient to reconstruct the cell model as an assembly. The reconstructed basic production cell, with the provisions for mounting the dual-arm Yaskawa robot and without the protective acrylic shield-wall is shown in Figure 32.

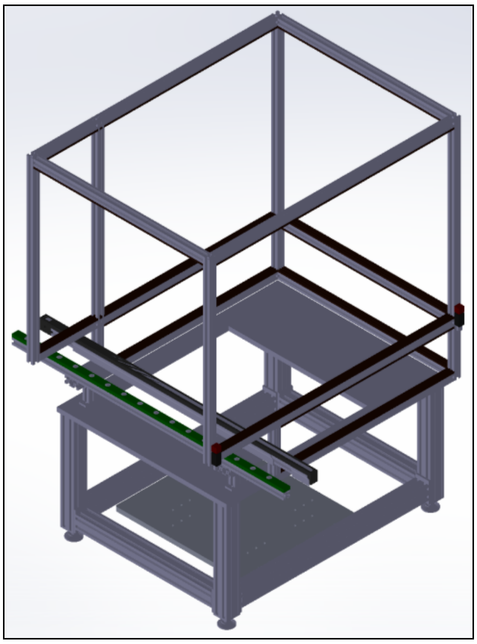
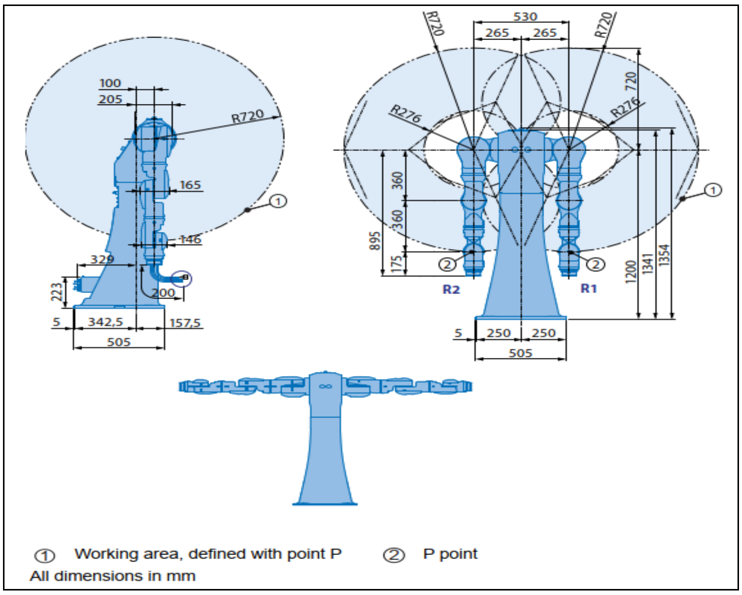


***Figure 32** Reassembled Basic cell with robot base plate, and acrylic sheets removed*

This is the first version (Iteration 0) of the dual-arm robot cell, as there is provision to mount the base of the robot below the cell (the SDA10F model). The robot support structure had to be lowered because the manipulator had a vertical height of 1354mm and the heights of the base joints of the dual arms were 1200mm. Check the Figure 33.



① Working area, defined with point P ② P point
All dimensions in mm

***Figure 33** Yaskawa SDA10F Dimensions and Reach [9]*

The rectangular slot on the support surface of the dual-arm station is present because, it was a portion of the surface which was water cut, and the cut-portion of the surface, was used to form the support structure for the base of the Yaskawa SDA10F. Additionally it provides the slot/ opening for the body and the arms of the dual-arm manipulator to be inside the required working area. Check Figure 34.

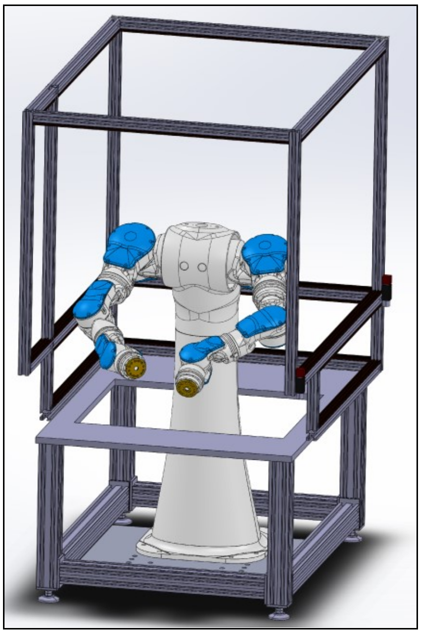


***Figure 34** Reconstructed cell with the SDA10F manipulator*

The dual-arm station has undergone four major iterative updates in order to overcome certain shortcomings in their current form or to enable the addition of certain features and functionalities. They are listed in the Table 1.

Table 1 *Iterative changes in design made to the dual-arm robot station*

Iteration Number	Features	Changes made	Functionality	Figure number
0	Cell has provision to support robot manipulator.	Cell reconstructed in SolidWorks for Catia. Surface for originally mounting the SCARA was repurposed to be the floor, for the base of the SDA10F.	Robot arms and the external axis joining the two arms can work within the confines of the cell.	Figure 32
1	Additional elementary storage shelves.	The racks were added to iteration 0.	The robot could now use the shelves to load and unload the pallets as storage.	Figure 35
2	Increased work area for the dual-arm manipulator.	The workstation was pushed back by 400mm from the main FASTory line. The position of the FASTory conveyor of the WS remains unchanged.	Increase in the work area for the dual-arm manipulator. Increased position configuration possibilities for the robot arms while loading/ unloading the pallet in the conveyor.	Figure 36
3	Increased safe operation area. Provisions for Mobile robot to enter work environment. Improved pallets storage. Updated design of	Extended the structural boundaries of the cell and removed a portion of the cell surface. 16 racks added to the shelves.	Robot able to make free rotations in the common external axis without collision with parts of the cell. Easy interaction with the mobile robot. More accurate loading/	Figure 37

	FASTory conveyor		unloading of pallets in the shelves	
4	Increased work area. Provisions for paper feeding element and paper holding basket.	The location of the shelves were moved 300mm outside from previous iteration. Dedicated positions for paper feeder and in-station basket holder provided	The support structure of shelves no longer interfere with the robot operation while performing dual-arm handling of pallets. Automatic paper feeding mechanism is possible to be implemented inside the cell. Baskets containing drawings and empty basket can be stored in the cell, before moving it to and from the mobile robot	Figure 38

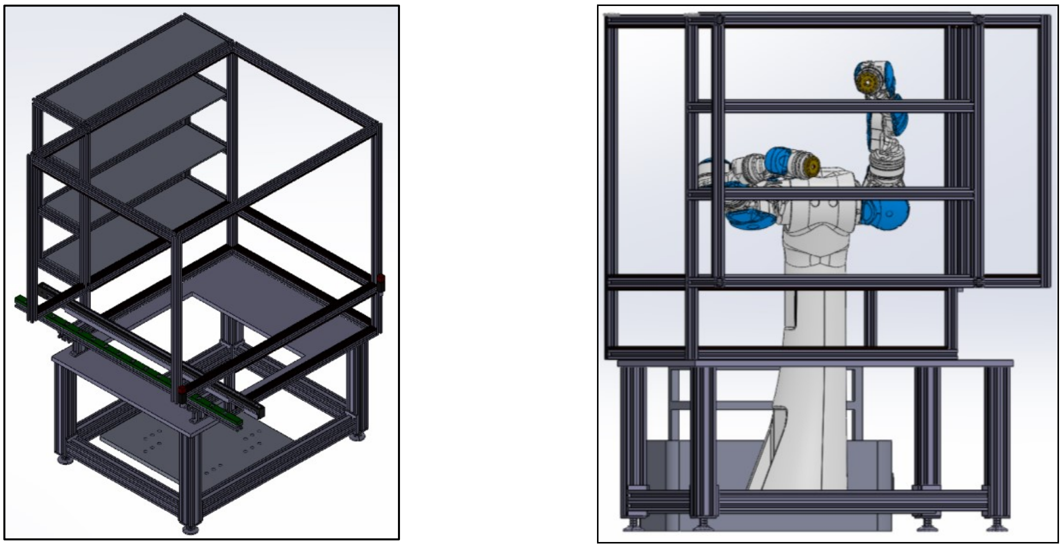


***Figure 35** Cell Design- Iteration 1 (left); preliminary visualization of dual-arm manipulator in the cell (right)*

Figure 36 *Cell Design- Iteration 2*

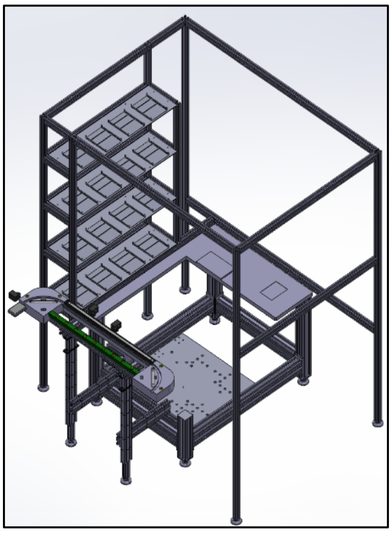


Figure 37 *Cell Design- Iteration 3*

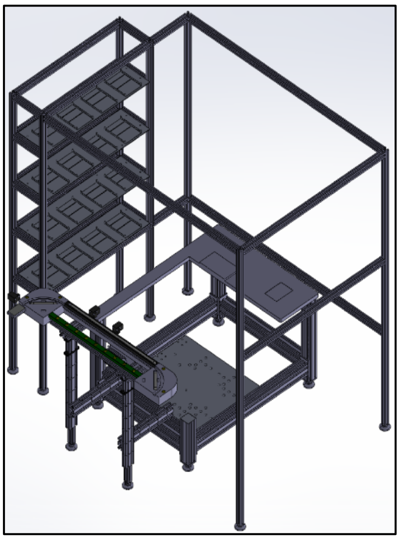


Figure 38 *Cell Design- Iteration 4*

The final iteration of the cell design incorporates all the necessary features and functionalities, required of the dual-arm robot station. It enables:

- The robot to interact easily with the pallets and its elements (loading/ unloading canvas paper) in the conveyor.
- The simple removal and addition of the pallets from the conveyor and the storage stand.
- The easy transfer of the canvas paper containing the drawn mobile to the basket in the workstation.
- The transfer of filled basket to the autonomous mobile robot and the retrieval of the empty basket from the mobile robot.
- Handling the paper being delivered by the paper feeder mechanism, and place it on the pallet in the conveyor line and lock it in position by placing the metallic paper clamp.

This final iteration of the cell fully combines the features of both the original main cell and buffer cell, and adding additional capabilities, wherein it interacts with a mobile robot which takes away the finished product.

3.3 End of Arm Tooling Design and Consideration

The selection of the End of arm tooling (EOAT) was also an iterative process and had direct and indirect implications towards the design evolution of the dual-arm work station, discussed in the previous section 3.2. The objectives and the requirements pertaining to the EOAT considerations were described in the section 1.3.

3.3.1 Tool Base

The robot is required to perform four specific operations. The interaction points for the dual-arm robot are distributed all around the cell (shown in Figure 36). This creates a need for the mounting of several end effectors on the arms of the manipulator. The initial consideration was to implement an Automatic Tool Changer (ATC), wherein create modular attachments for all the tools with correspondence with commercial ATCs [54]. This however leads to complications as the commercially available ATCs have niche application or are too bulky to be implemented and create space constraints in the work stations and reduce the payload capability of the individual robot arms. The concept was downscaled and a modular Hexagonal mounting, capable of holding six individual tools was designed and fabricated (shown in Figure 39).

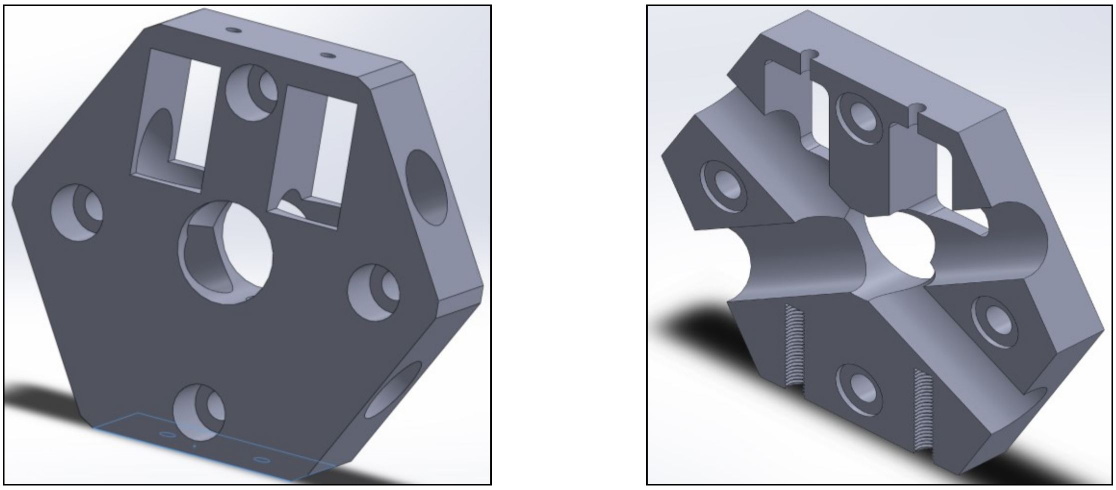


Figure 39 *Tool Holder with provisions for mounting the end-effectors (left); cross-sectional view of the tool-holder*

This current model of the tool holder can enable the individual arms of the dual-arm manipulator, to utilize the required tool by the rotation of their T-axis. The Figure 40 shows the utilization of the tool holder with the dual-arm manipulator in a previous iteration of the EOAT combination. The current iteration of tooling present in both the arms of the manipulator will be explained in the following sub-sections

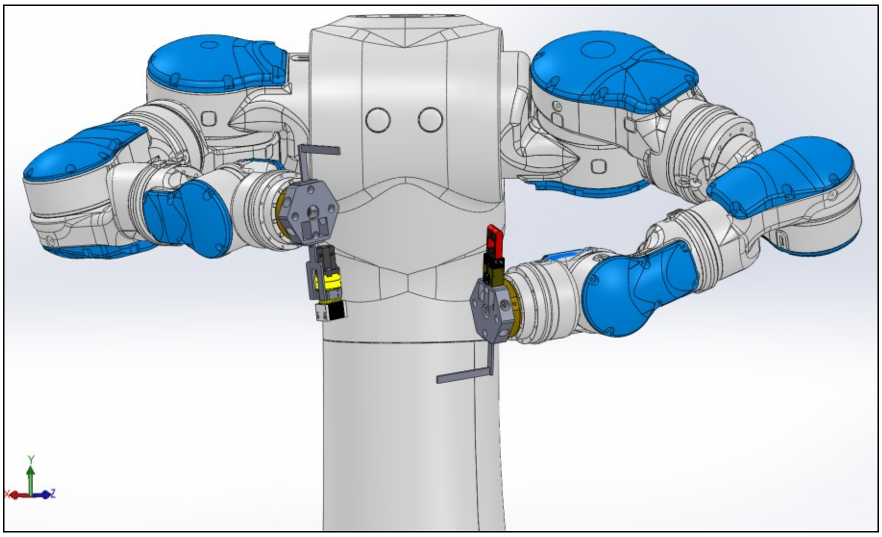


Figure 40 *Preliminary iteration of tool holder and end-effector combinations*

3.3.2 Bi-manual Manipulation of the FASTory Pallets

The pallets of the FASTory line is used the base on which the canvas paper is transferred around the FASTory line, through the conveyors systems. The pallet along with the paper-holder is shown in Figure 41.

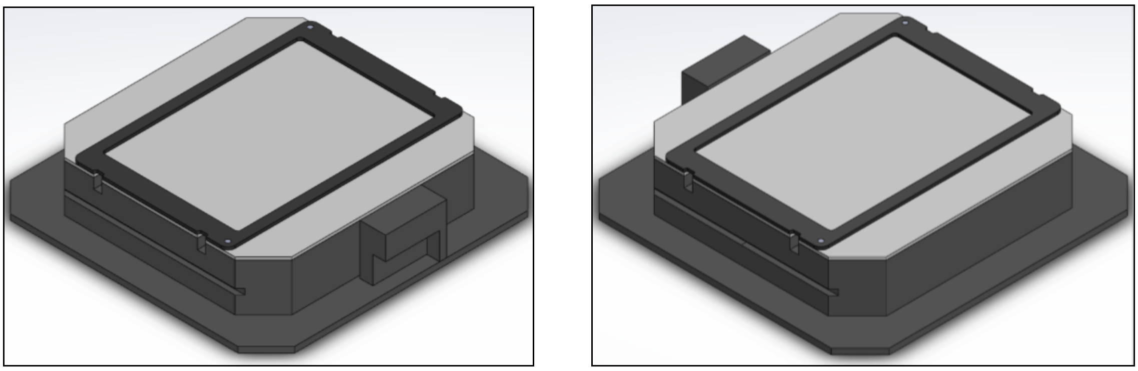


Figure 41 *FASTory Pallet with paper holder- symmetric Lateral Slots depiction*

The FASTory pallets have two symmetrical slots on either side of the pallet, which was originally utilized by the 4DOF manipulator system in the buffer cell (shown in Figure 42).

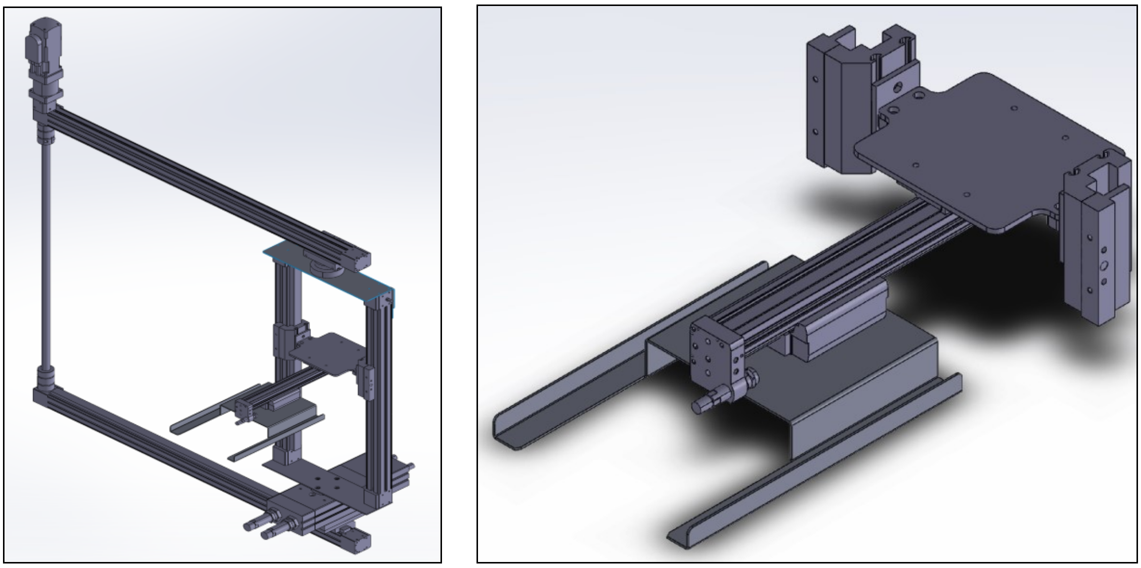


Figure 42 *Original Buffer station Manipulator with Cartesian links and fork (left); Fork previously used to handle pallets (right)*

The EOAT was an individual block which resembles the functionality and appearance of a fork. The manipulator slides the fork into the slots of the pallets which weigh roughly around 2.7kgs (with the paper holder). The limbs of the fork were thin enough to slide into the 3.75mm lateral slots on the pallet and sturdy enough to hold the pallet, and transfer it to the rack (in the buffer cell, as shown in Figure 26) from the conveyor and vice-versa, as required.

The current application involves the Bi-manual handling of the pallet. Two fingers resembling a cantilever L-beam are individually fitted to each tool holder (check Figure 43), in each arm of the manipulator, respectively (refer Figure 40). The modularity of the tool holder enables it to be used interchangeably.

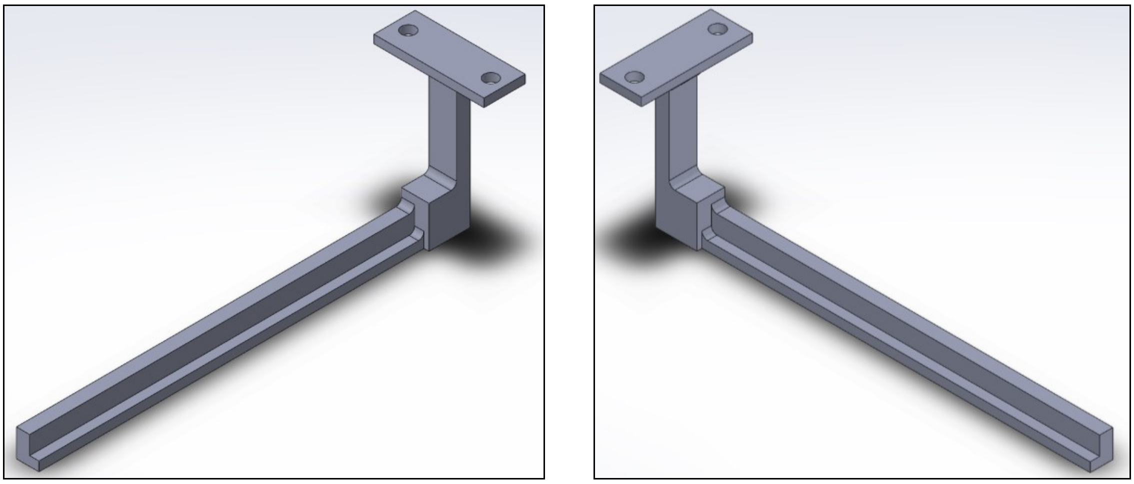


Figure 43 *Pallet holder finger- right finger (left); Pallet holder finger- left finger (right)*

The original consideration was to use a heavy duty parallel gripper to handle the pallets, but the two finger option was used for the following reasons.

- Ease of fabrication
- Cheapness and replicability
- Demonstration of Bi-manual robot operation
- No additional requirements for pneumatic lines, I/Os, power supply, etc

The robot can lock and hold the pallet by moving the individual fingers, towards and away from each other, and can move the object similar to an anthropomorphic implementation.

3.3.3 Handling the Paper clamp/ holder of the pallet.

The removal and repositioning of the paper clamp (as shown in Figure 44), from the pallet (as shown in Figure 40) was initially performed by a specialized EOAT in the main cell. The paper clamp is held in position by a 2X2 array of magnets on the pallet. The canvas paper can be removed or positioned, only after the paper clamp is removed.

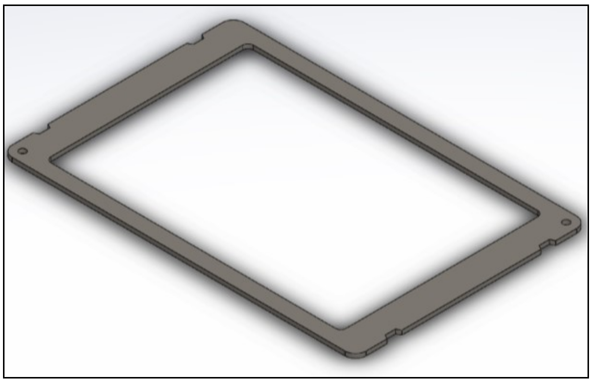


Figure 44 *Paper Clamp*

The originally used SCARA manipulator and the specialized tool initially designed, to handle the clamp are shown in Figure 45.

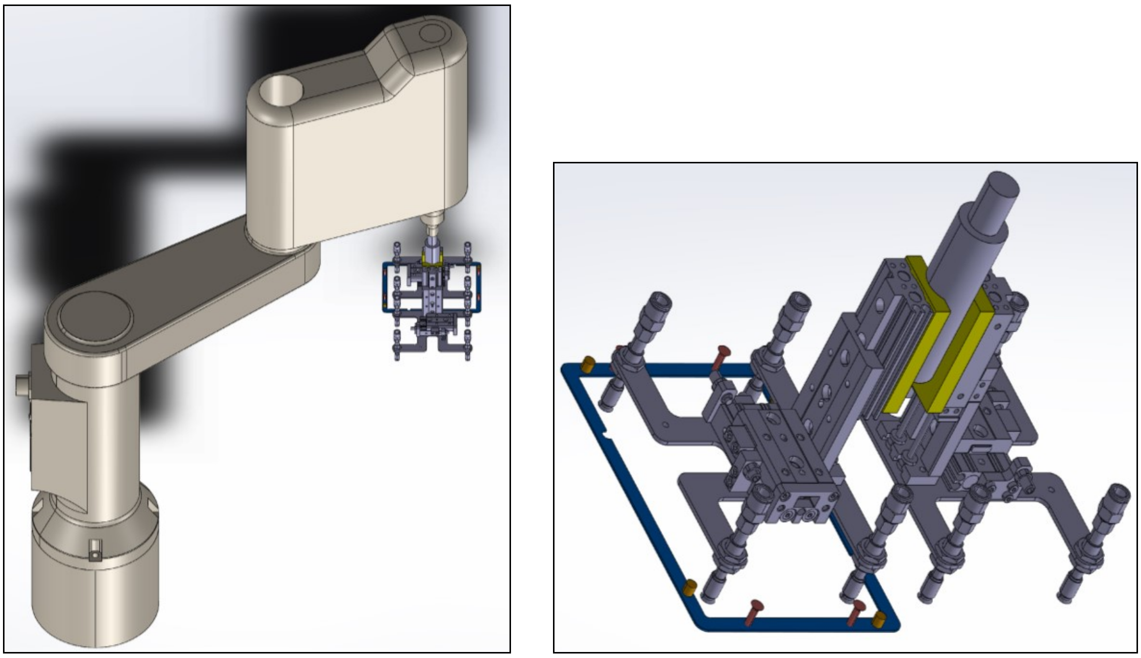


Figure 45 *SCARA manipulator with original tooling (left); The EOAT displayed in detail (right)*

The tool was designed to simultaneously remove the clamp and the paper in one robot motion. The tool has two sets of gripping elements. It has two sets of parallel grippers to grip the paper clamp and the paper is handled by means of integrated vacuum suction cups. The clamp was removed by two parallel grippers and the suction cups hold on to the canvas paper. The end-effector is then rotated 180° and identical empty paper and clamp are fitted to the empty pallet. The robot then moves to a drop off location and releases the vacuum in the paper holding suction cups, dropping the paper containing finished product. The process of handling the clamp and the canvas paper was done in a single operation. However, to reduce the complexity of the tooling, the process was separated in to separate operations.

The handling of the paper holder is explained in this section and two options were considered. The first option was to utilize a permanent magnetic gripper to handle the paper clamp, as it was made of a ferrous material. The working principle of the magnetic gripper was briefed in section 2.3.3. The gripper is shown in Figure 46 with the required attachment to mount it to the tool base, for this implementation.

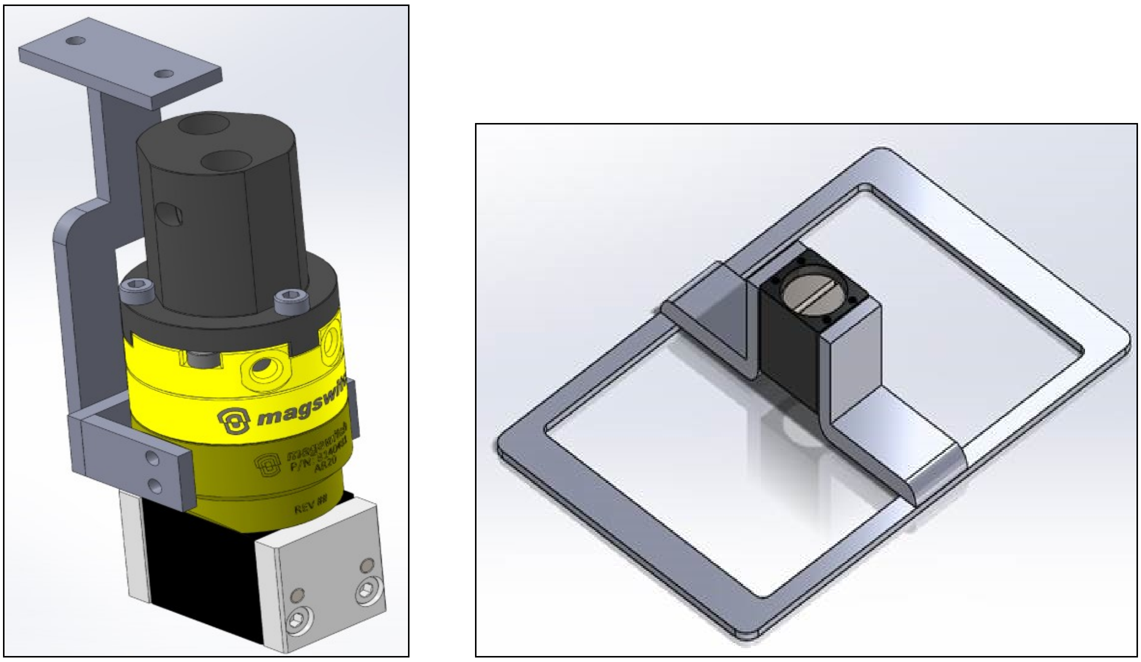


***Figure 46** Magnetic gripper with attachment to integrate with tool holder (left); the pole shoes (gripping surface) for the gripper with the paper clamp (right)*

The magnetic gripper was an attractive option to implement as it was compact and very straight forward in its application. However, the reasons for not implementing a magnetic gripper as opposed to the other solution are:

- Magnetic grippers were an expensive alterative
- The small deviations in the pallet position (pallet bounce, when stopped in conveyor zones)
- Residual magnetism

This has resulted in the utilization of a simplified version of the original EOAT used in the main cell. The setup is essentially two parallel grippers arranged as shown in the Figure 47, which opens and closes to grasp the paper clamp.

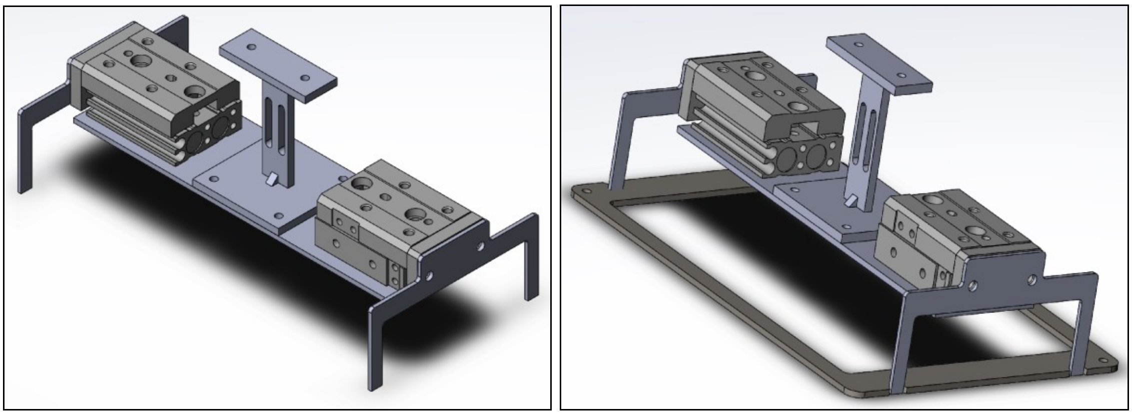


Figure 47 *Finalized EOAT with attachment to integrate with tool holder (left); EOAT grasping the paper clamp*

The simplified end-effector is utilized to remove the paper clamp alone. The paper handling will be explained further in section 3.3.4. The reasons for preferring this solution over the magnetic gripper implementation are:

- Cost factor/ components readily available
- Lock in mechanism to handle the paper clamp regardless of pallet bounce
- No residual magnetism.

3.3.4 Basket and Paper Handling

The handling of the basket containing the drawings of the finished mobile phone models (see Figure 48), and the actual canvas paper for drawing the models are handled by a single gripping element. A parallel gripper with specialized fingers was the end-effector of choice for performing this group of operations.

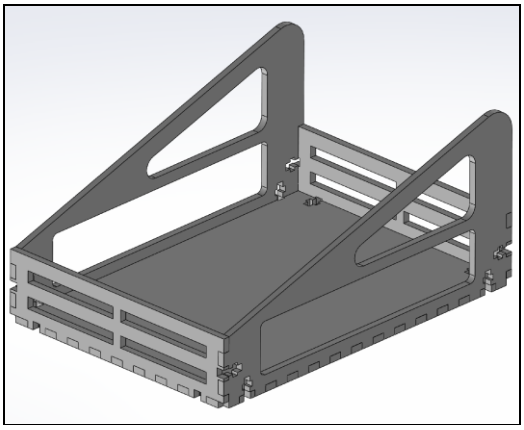


Figure 48 *Basket for Paper containing finished product*

The selected parallel gripper has a payload capacity of 1.75kg and the more important feature of permissible finger length, which is up to a 100mm. The Gripper and the figure is depicted in Figure 49. The length of the designed finger profile is 83.6mm, and the triangular contour has similar dimensions to the triangular slot in the basket as shown in Figure 48 (with a very narrow clearance fit).

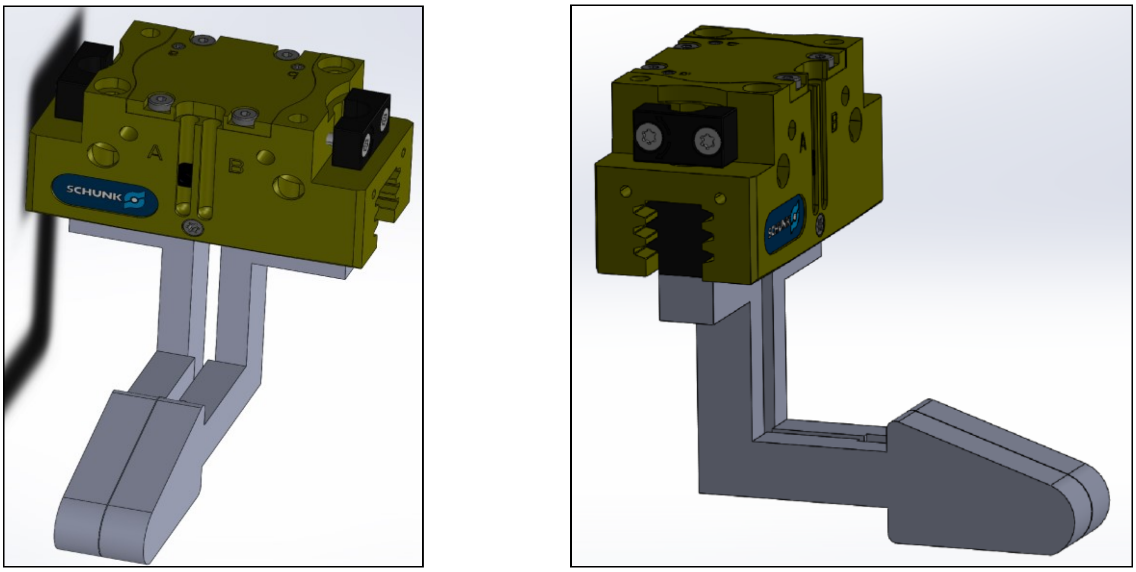


Figure 49 *Parallel gripper with specialized fingers for handling the basket template and the canvas paper*

The provision of the triangular extrusion provides a locking mechanism to further hold the pallet in place, while the major gripping of the basket happens in the horizontal stem of the gripper between the gripper housing and the triangular profile (see Figure 50).

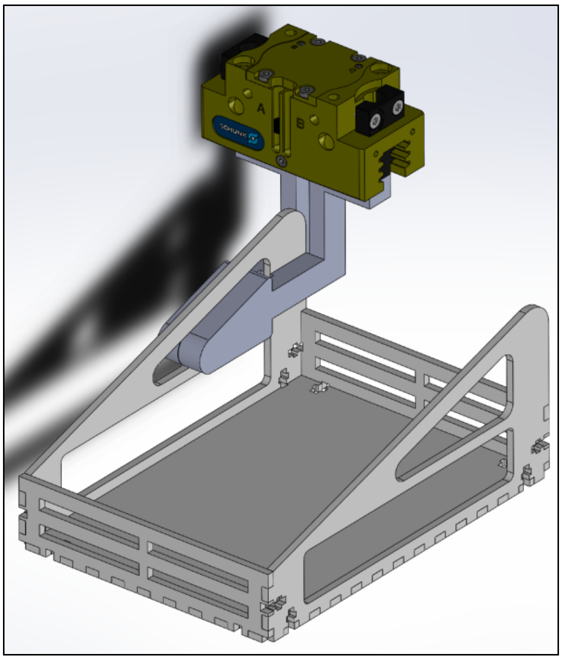


Figure 50 *Gripping action of the basket. Gripping surface and locking profile depicted*

The handling of the paper from the paper feeder in the cell to the pallet on the conveyor, and vice-versa, is performed by grasping the paper on the triangular profile of the fingers. The triangular portion of the fingers is covered with a material which increases the coefficient of friction without much wear. This enables the proper grasping of the deformable paper. A sweeping motion of the robot is essential for the proper laying of the paper onto the pallet before placing the paper-clamp. While removing the paper from the pallet, the right hand pallet finger is used to nudge the paper from the middle of the pallet, till it's sufficiently over the pallet's edge. The finger can then grasp the paper and place it on the basket. The utilization of the tools are cross functional and the dual-arm capability of the manipulator is an important factor, which enables the cross-functionality of tools from intended purpose. The next section discusses the tools layout in each arm and provides an overall description of the EOAT and manipulator capability.

3.3.5 EOAT Summary

The Right Hand Side (RHS) or the Arm-2 of the robot contains the EOAT required for partially handling the Pallet (bimanual operation), and the handling of the basket and the canvas paper. The Light Hand Side (LHS) or the Arm-1 of the robot contains the tooling required to partially handle the pallet and to handle the paper-clamp on the pallet. The tooling for both hands are attached to the manipulator by the modular tool holder. The setups are shown in Figure 51.

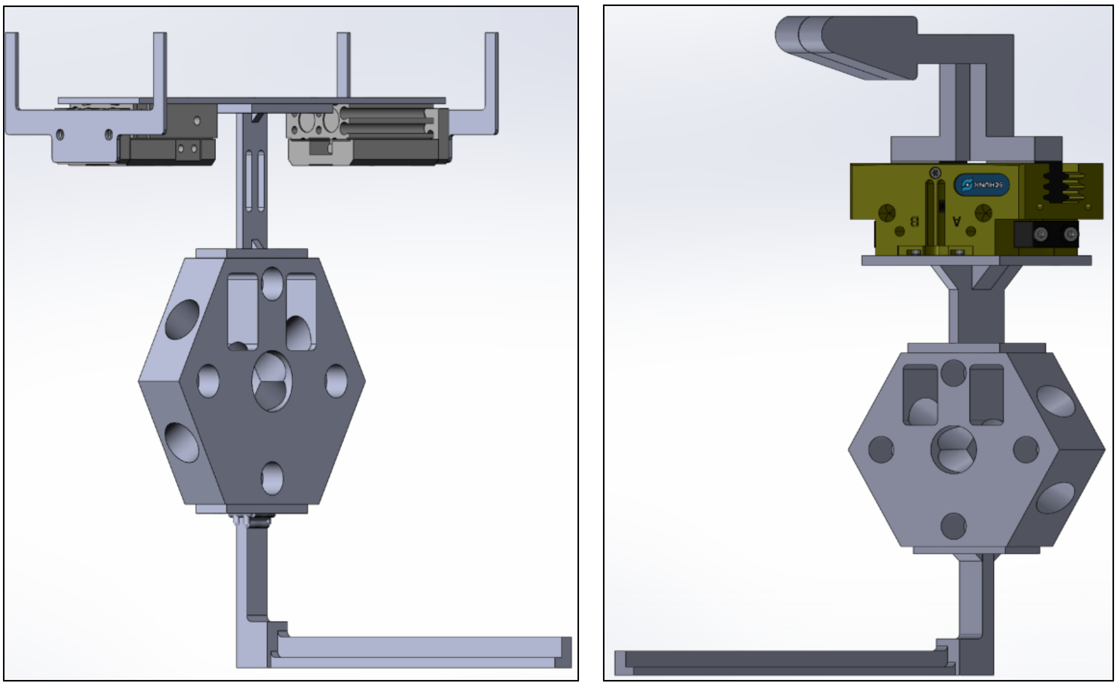


Figure 51 *LHS Tooling (Left); RHS Tooling (Right)*

The following table discusses capability of the dual arm manipulator, which is essentially two individual 7DOF manipulators connected to a common external axis/ base with 1 DOF. All three individual modules have their own I/O and pneumatic provisions. However, the table only considers the two arms as they meet the required I/O and pneumatic supply demands. The table also highlights the functionality and the requirement of the individual elements to perform the tasks. The external axis/ base is considered only as a common moving element, and is hence omitted from the comparison due to redundancy. Check **Error! Reference source not found.**.

Table 2 *Comparison of the Manipulation capability of the dual-arm robot*

S. No	**Features**	**ARM-1 LHS**	**ARM-2 RHS**
1	Manipulator Payload capacity	10kg	10kg
2	EOAT mass with tool holder and without payload	1.2kg	1.1kg
3	I/Os Available	12	12

4	I/Os Required	2	2
5	Pneumatic lines available	2	2
6	Pneumatic lines required	2	2
7	Pallet Handling (1.75kg) - Loading/ Unloading from the conveyor and storage	YES Dual-arm Bi-manual manipulation	YES Dual-arm Bi-manual manipulation
8	Handling the Paper clamp/ holder of the pallet.	YES Two pneumatically actuated parallel grippers grasp and lift the clamp	NO
9	Basket and Paper Handling	YES (partial) The LHS finger is used to slightly slide the paper over the edge of the pallet, while removing the finished drawing. This enables the gripper finger to grasp the paper.	YES • Parallel gripper with specially designed Fingers to grasp and lock the basket in position • The triangular profile is coated with special material to enable the grasping of paper without wearing out

3.4 Offline Simulation- MotoSim EG VRC

MotoSim EG VRC is the offline programming software where the operations of the Yaskawa SDA10F and the FASTory line are programmed and simulated. The environment for the dual-arm robot station and all the other elements, including the EOATs, Model MiR with positional accuracy, Paper feeder mechanism, etc. are imported, and arranged; to represent the physical system

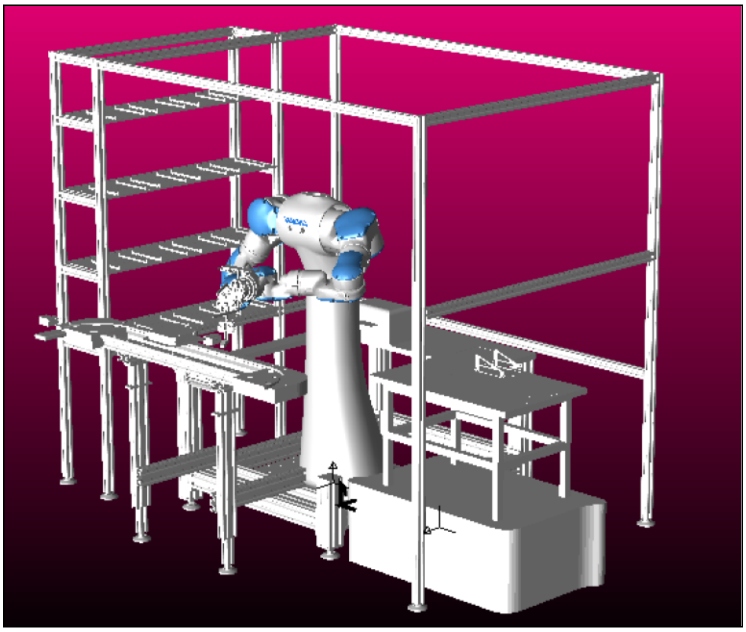


***Figure 52** Dual-Arm Robot Station in MotoSim*

The SDA10F robot and its corresponding controller (FS100) are initialized and integrated into the existing environment. The user interface of the robot Teach Pendant in the MotoSim environment is the same as the physical Teach Pendant and the programming language (Inform) is also the same. MotoSim EG VRC (Enhanced Graphics – Virtual Robot Control) is capable of the following functions:

- Fast setup and analysis of systems and their layouts. Models can be imported from external sources, additional in-software features for creating 3D models.
- The interface possesses convenient tools i.e. collision detection and control, soft limits, CAM functions, user defined 3D views and frames.
- Accurate cycle time analysis of the operations performed by the manipulator and defined elements in the environment.
- MotoSim contains a number of sample cells, demonstrating the execution of complex system configurations.
- Job transfer modules to transfer from one manipulator to another manipulator, which maybe replacing it.
- Simulations can be viewed without the need for installing licensed software in the form of web applications, AVI files and/or vPDF.

The software package provides us a multitude of useful tools to perform the offline simulation of all the operations of the dual-arm robot station. The next chapter focuses exclusively on the implementation of the operations in the MotoSim environment and breaking down the tasks and analysing the performance of the system.

4. IMPLEMENTATION

This chapter describes the implementation of the technology documented and the specialised tooling developed for the Dual-Arm robot station. The operations of the robot, the functionalities of the Dual-Arm station, and the interactions between the sub-systems inside the Dual-Arm station are the subjects of interest here. The implementation of the proposed solution and its various aspects are detailed using Unified Modelling Language (UML) to describe the features of the station.

The process capabilities and functionalities of the Dual-Arm robot station are described in the Use Case diagram, shown in Figure 53. The purpose of this use case diagram is to provide an overview of the system and to showcase its features. The dual-arm manipulator is the primary element which performs most of the tasks (processes) and is the primary or main actor. Whereas, the operator is an additional actor whose roles are secondary, as when compared to the dual-arm manipulator and does not have to be present at all times for executing the operations of the station. This highlights the autonomy of the Dual-Arm station and its ability to operate unsupervised (whenever required).

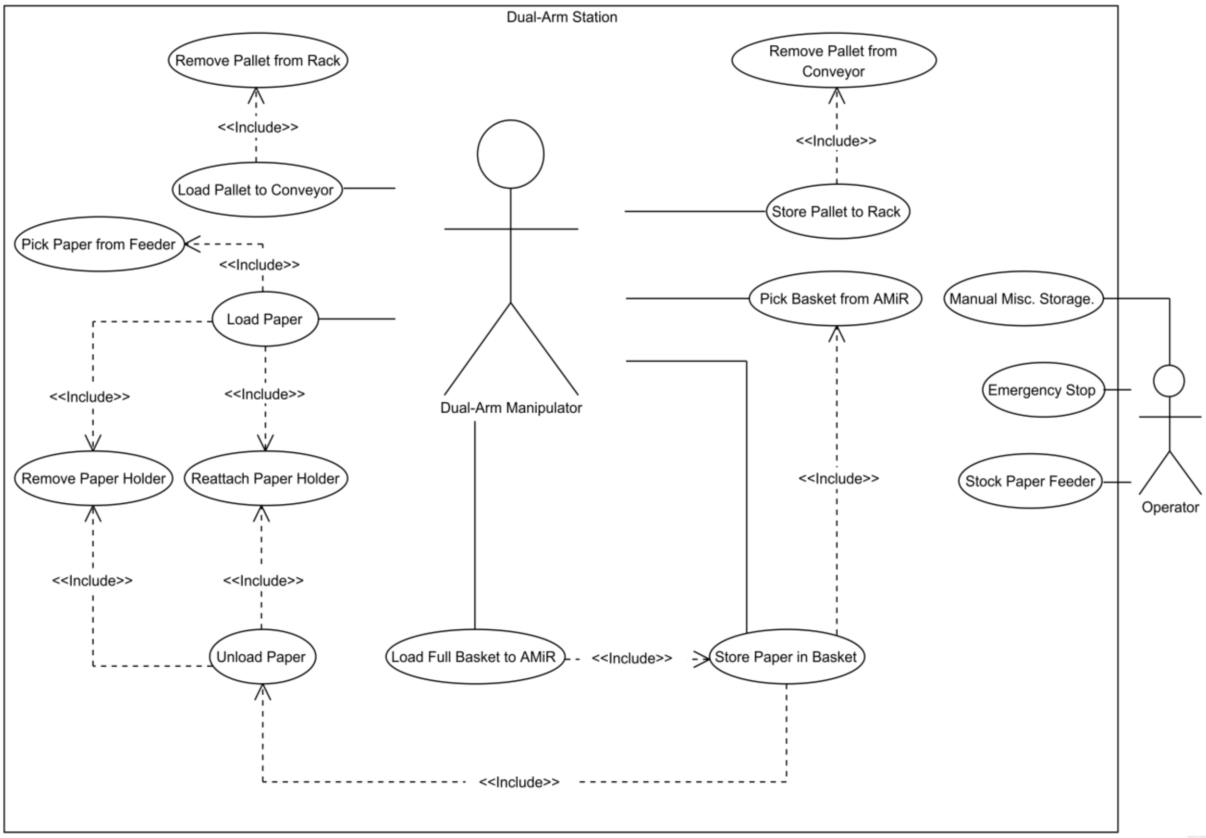


Figure 53 Dual-arm Station- Use Case Diagram

The Major Use Cases which are to be to be performed by the Dual-Arm station include:

- Loading the Pallet to the FASTory conveyor from the storage rack.
- Storing the pallet in the storage rack from the FASTory conveyor.
- Loading the empty paper to the pallet on the FASTory line.
- Retrieving the paper containing the drawn model from the Pallet.
- Loading the basket containing the drawn models to the Autonomous Mobile Industrial Robot (AMiR).
- Retrieving the empty basket from the AMiR.

These primary use cases are the main functionalities of the Dual-Arm station and are performed by the dual-arm manipulator. However, these Use Cases are dependent on the successful performance of several secondary use cases, which are also mostly performed by the dual-arm manipulator, sequentially, as part of the process. The inter relationship between these use cases are clearly documented in Figure 53. The role of the operator is very limited and is associated with the tertiary functionalities of the cell. The primary use cases and their dependencies are explained in detail and their execution in the simulation environment are documented in the following portions of this chapter.

4.1 Handling of Pallets

Controlling the number of pallets in circulation in the FASTory line is one of the functions of the Dual-Arm station. The dual arm manipulator is responsible for loading the pallet to the conveyor from the storage rack, and removing the pallet from the conveyor and placing it in the storage rack, similar to an AS/RS system. The operations to be performed by the robot are controlled by the Inico S1000 PLC, by utilizing I/O connections between the robot controller and the RTU.

Based on the requirement of the FASTory system and the logical determination of the knowledge base, the orchestrator changes the states of the digital output in the Inico S1000 which is the RTU for the Dual-Arm station. This section of the chapter documents the behaviour of the system when the Pallet Handling (Loading to the conveyor/ Removal from the conveyor) command is invoked by the Inico and there is a focus on the individual actions performed by each arm of the dual-arm manipulator, with respect to the FASTory environment.

4.1.1 System Behaviour and Interactions

This sub-section describes the interactions between the various elements of the Dual-Arm station which are involved in the handling of the pallets. The interactions are represented by sequence diagrams to showcase the exchange of messages and system status data between the essential elements, which in these use cases are the FASTory Conveyor, the Inico S1000 and the Robot Controller.

The sequence of operations performed by the Dual-Arm station for loading of the pallet to the FASTory conveyor from the required storage rack is shown in Figure 54. Whereas, the sequence of operations for loading the pallet to the required storage rack from the FASTory conveyor is shown in Figure 55.

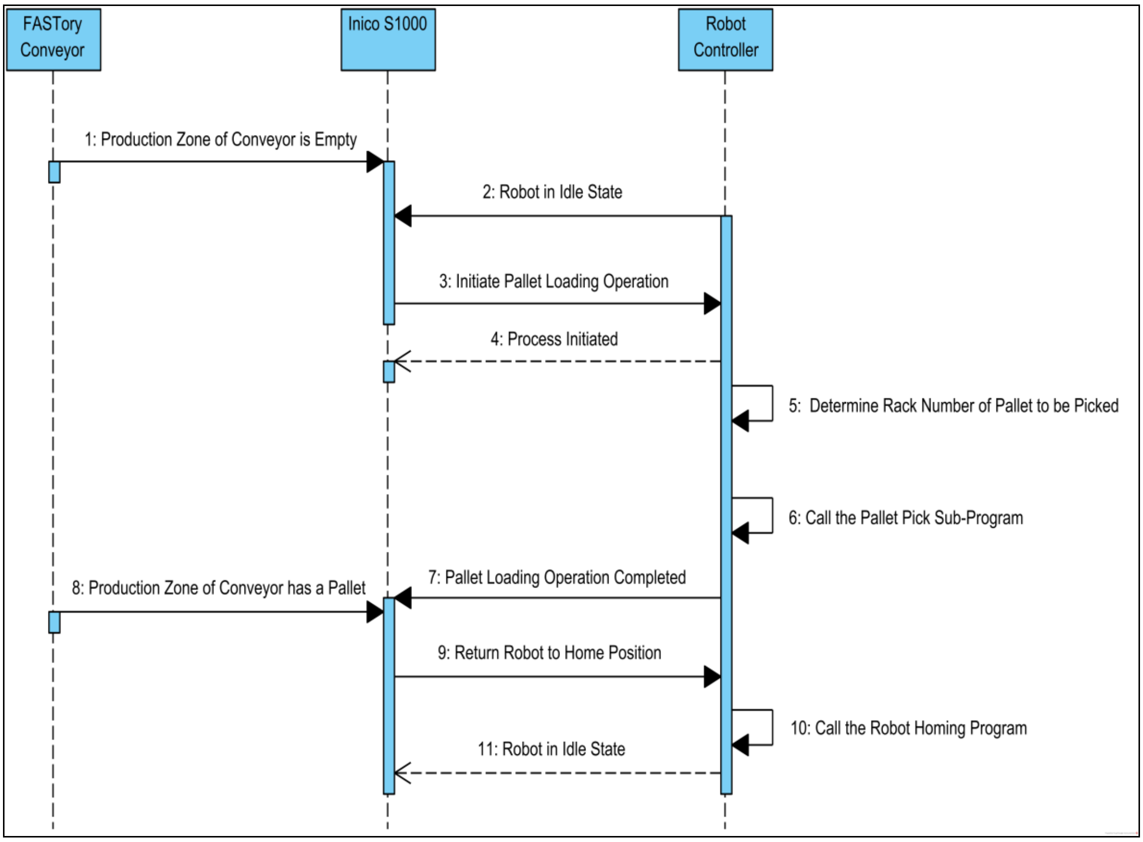


***Figure 54** Loading Pallet to the Conveyor from the Storage Rack (Sequence Diagram)*

When the process of loading the pallet to the conveyor is to be initiated, the RTU checks for the digital I/O signals which are inputted from the FASTory conveyor and the Robot Controller stating that the production zone in the conveyor ‘Z3’ is empty (sensor output data) and that dual-arm manipulator is in the ‘idle’ state (Home position), respectively.

The RTU then sends the signal to the Robot Controller to initiate the pallet loading operation. The RTU gets a response from the Robot Controller in the form of a digital input that the state of manipulator has changed from 'idle' to 'active' to denote that the process operation has begun. The Robot Controller calls the sub-program for removing the pallet from the most recently stored slot in the rack. The rack details and target data are stored in the internal registers of the robot and are constantly updated when the pallets are loaded or unloaded from the rack. The robot gets the target values of the rack from which the pallet is to be picked and performs the picking operation. It then places the pallet on the conveyor and sends out a process completed signal to the RTU, the RTU gets a confirmation signal from the FASTory conveyor (sensor output), that a pallet is in the Production zone. The RTU then instructs the robot controller to return to the Home position and once the controller is in the 'idle' state, it generates a digital output to the RTU, signifying an end to the process.

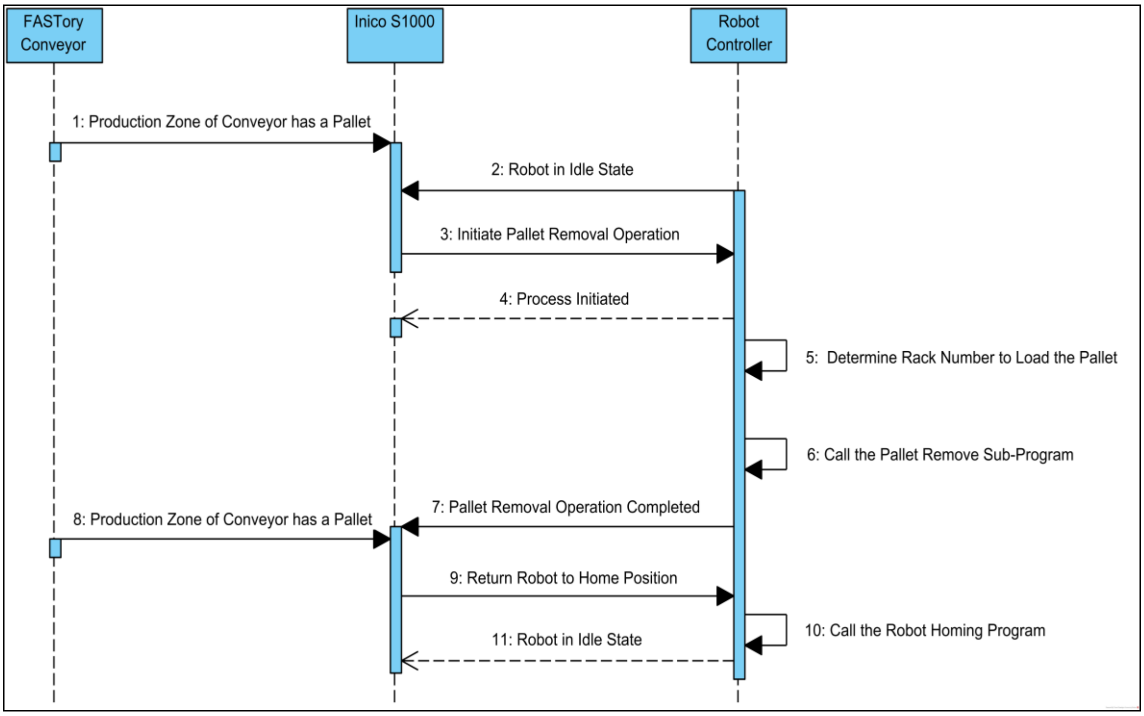


***Figure 55** Loading Pallet to the Storage Rack from the Conveyor (Sequence Diagram)*

The sequence of actions to be performed by the elements of the Dual-Arm station for loading the pallet to the storage rack from the FASTory conveyor have a similar logic, but in the reverse sequence as shown in Figure 55. When the process for storing the pallet is to be initiated, the RTU checks for the digital signals signifying that a pallet is present in the production zone 'Z3' of the FASTory conveyor (sensor output data) and the Robot Controller stating that the dual-arm manipulator is in the ‘idle’ state (Home position). The RTU then invokes the dual-arm robot station to perform the pallet storage operation by means of a digital signal. The RTU gets a response from the Robot Controller in the form of a digital input that the state of manipulator has changed from ‘idle’ to ‘active’ to denote that the process operation has begun. The Robot Controller then calls the pallet storage sub-program to remove the pallet from the FASTory conveyor and store in the newest available slot in the storage rack. The rack details and target data are stored in the internal registers of the robot and are constantly updated when the pallets are loaded or unloaded from the rack. The robot gets the target values of the rack in which the pallet is to be stored and performs the picking operation from the conveyor. It then places the pallet on the specified rack and sends out a process completed signal to the RTU, the RTU gets a confirmation signal from the FASTory conveyor (sensor output), that the pallet is absent in the production zone. The RTU then instructs the robot controller to return to the Home position and once the controller is in the ‘Idle’ state, it generates a digital output to the RTU, signifying an end to the process.

4.1.2 Manipulator Behaviour and Interactions

This sub-section describes the interactions between the internal elements of the dual-arm robot and the FASTory conveyor, and their involvement in the handling of the pallets. The interactions are represented by Activity diagrams showcasing the actions performed by the individual arms and the base axis of the dual-arm manipulator. The diagrams represent the workflow of the process by breaking it down to the stepwise execution of individual actions.

The sequence of operations performed by the Dual-Arm station for loading of the pallet to the FASTory conveyor from the required storage rack is shown in Figure 56. Whereas, the sequence of operations for loading the pallet to the required storage rack from the FASTory conveyor is shown in Figure 57.

The sequence of actions represented in these activity diagrams for the respective nature of the pallet handling process and the diagrams are self-explanatory in nature. The idea behind using these diagrams is to highlight the synchronized motion of the dual-arms and the base of the manipulator as they perform their individual operations with respect to each other.

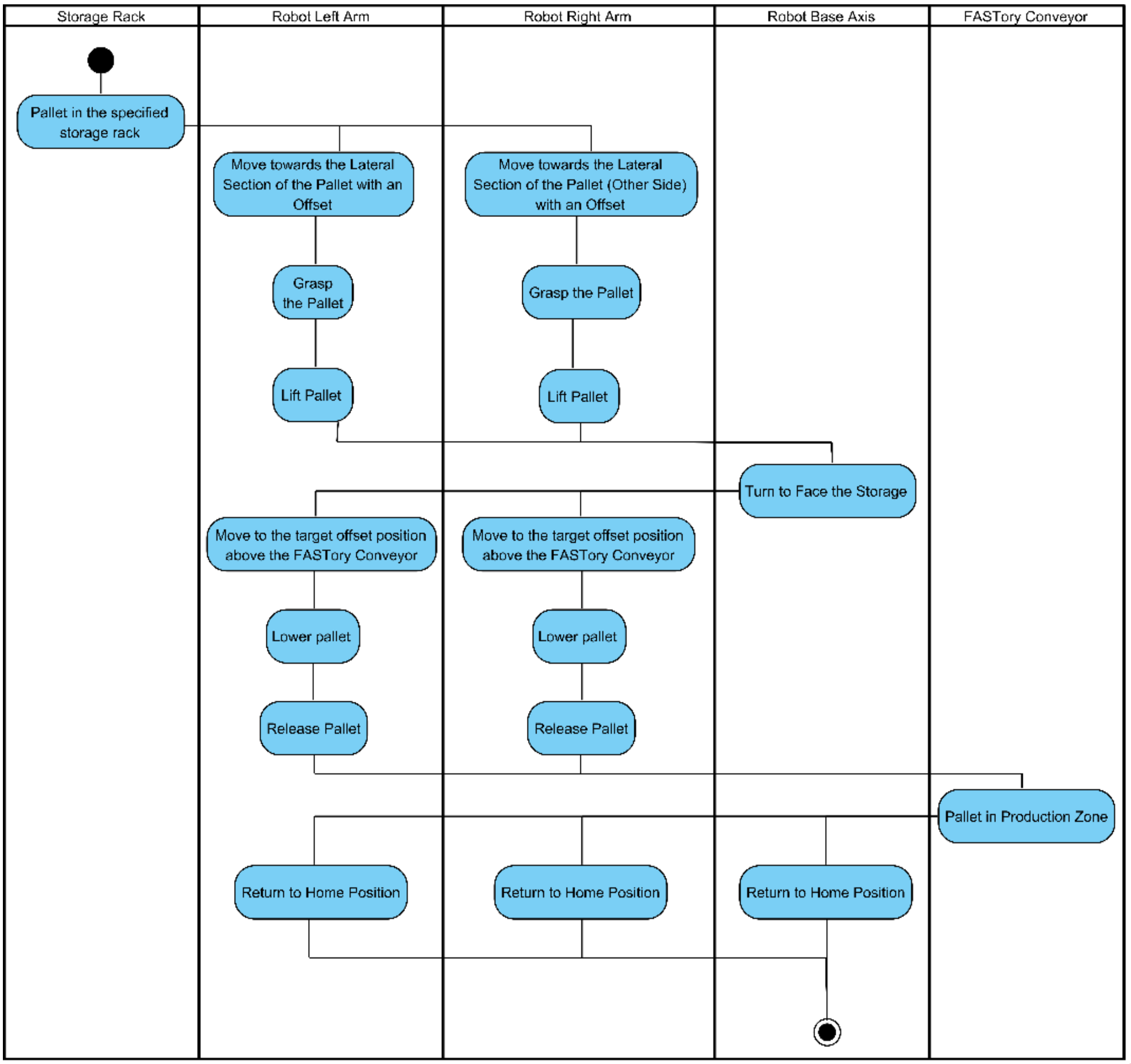


Figure 56 *Loading Pallet to the Conveyor from the Storage Rack (Activity Diagram)*

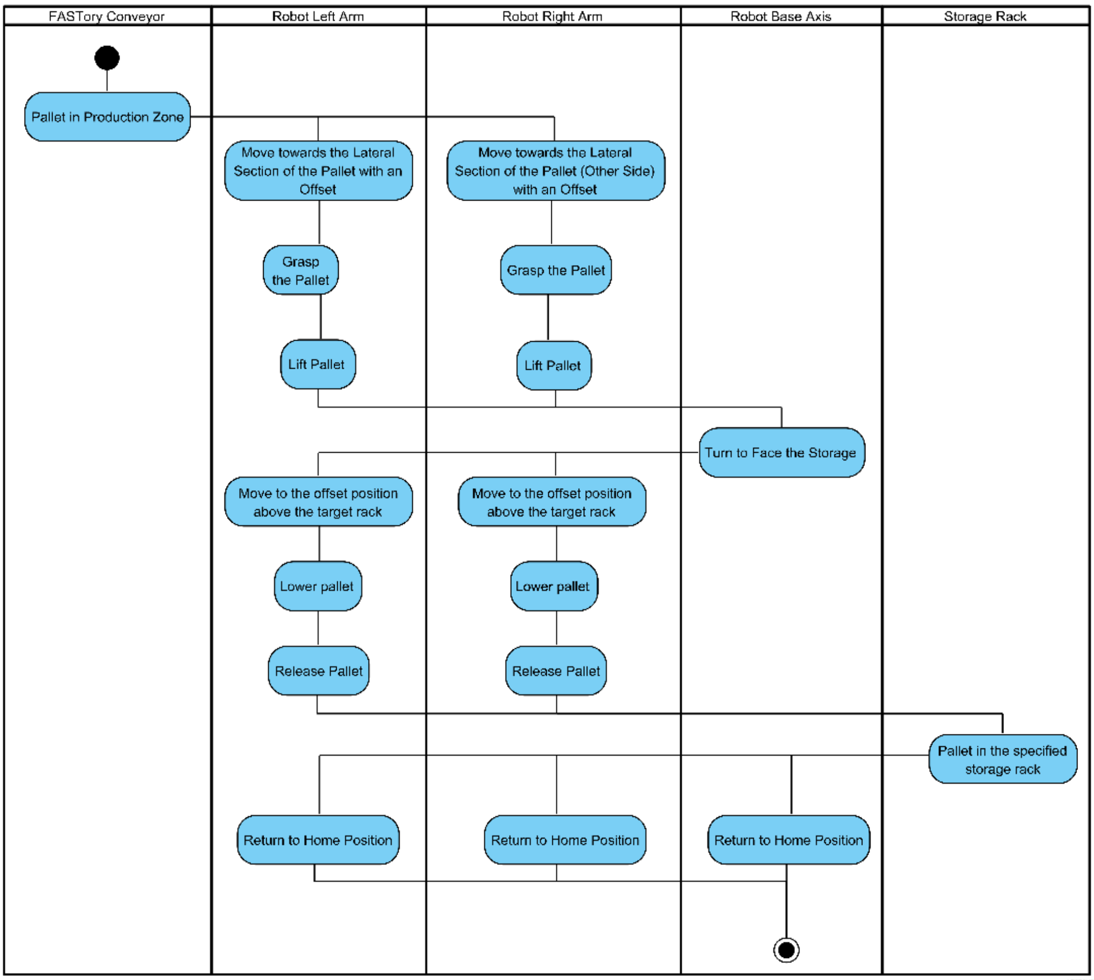


Figure 57 *Loading Pallet to the Storage Rack from the Conveyor (Activity Diagram)*

4.2 Handling of the Production Paper

The paper is the canvas on which the mobile phone components are drawn, by the production cells, to symbolise the assembly process of the various models of the mobile phone. The Dual-Arm station is responsible for delivering the paper to the pallet from the paper feeder and to retrieve the papers containing the drawn mobile phone components from the pallet and loading it to the storage basket, which contains the current production batch of mobile phones. The process of loading/ removing the paper is complicated by the additional handling requirement of the paper holder/ clamp, as it should be removed and replaced during both the operations.

This section of the chapter documents the behaviour of the system when the Paper Handling (Loading to the pallet/ Stored to the basket) command is invoked by the Inico and there is a focus on the individual actions performed by each arm of the dual-arm manipulator, with respect to the FASTory environment.

4.2.1 System Behaviour and Interactions

This sub-section describes the interactions between the various elements of the Dual-Arm station which are involved in the handling of the production papers. The interactions are represented by sequence diagrams to showcase the exchange of messages and system status data between the essential elements, which in these use cases are the FASTory Conveyor, the Inico S1000, the Robot Controller, the Paper Feeder and the Paper Basket.

The sequence of operations performed by the Dual-Arm station for the loading of the production paper to the pallet from the paper feeder is shown in Figure 58. Whereas, the sequence of operations for loading the production paper, containing the drawings of the mobile phone component to the storage basket from the pallet is shown in Figure 59.

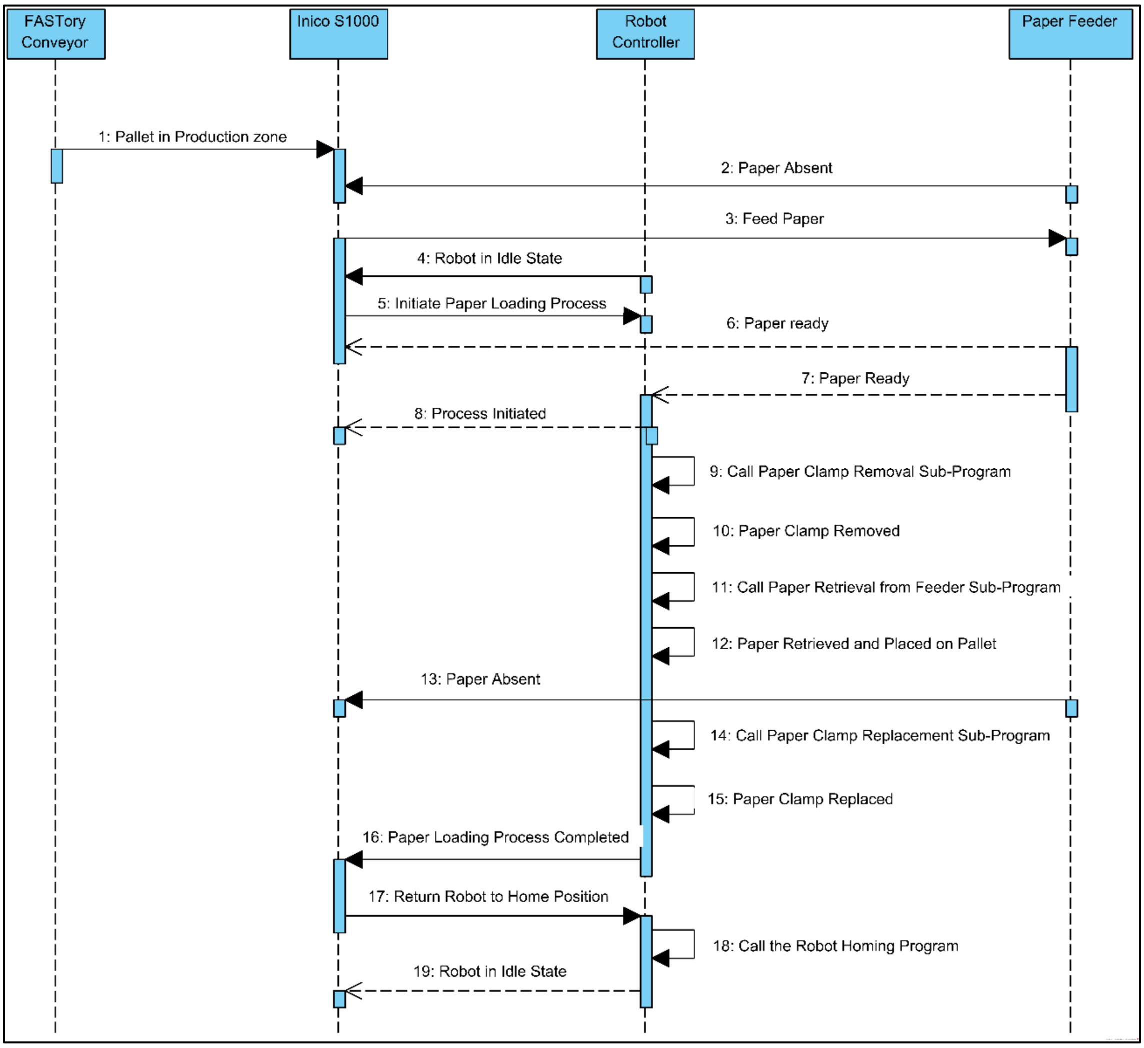


Figure 58 *Loading the paper to the pallet from the paper feeder (Sequence Diagram)*

When the process of loading the paper to the pallet is initiated, the RTU checks for the digital I/O signals which are inputted from the FASTory conveyor (sensor output data) stating that the pallet is in the production zone, and the paper feeder stating whether there is a single paper ready for use. If there is no paper ready for the manipulator in the paper feeder, then the RTU instructs for a paper to be fed. Once the paper is fed, the feeder sends a response to the RTU in the form of a digital output (sensor data) and the RTU checks if the manipulator is in the 'idle' state. Then the RTU invokes the manipulator to perform the paper loading process to the pallet, from the paper feeder and the state of the robot is changed to 'active' from 'idle'. The Robot Controller calls for the 'paper clamp removal' sub-program and the left arm of the manipulator containing the dual cylinder parallel gripper, grasps the clamp and removes it. After the paper clamp is removed from the pallet, the Robot Controller calls for the 'paper retrieval from the feeder' sub-program, the right arm of the manipulator grasps the paper and places it on the pallet.

After this operation is executed, the Robot controller calls the ‘paper clamp replacement’ sub-program and the clamp held in the left arm is replaced on the pallet, locking the production paper in place; subsequently, the paper feeder notifies the RTU that the paper has been removed. The paper loading process (containing multiple sub-processes) is executed and the Robot Controller notifies the RTU of the current state of the system. The RTU then instructs the robot controller to return to the Home position and once the controller is in the ‘idle’ state, it generates a digital output to the RTU, signifying an end to the process.

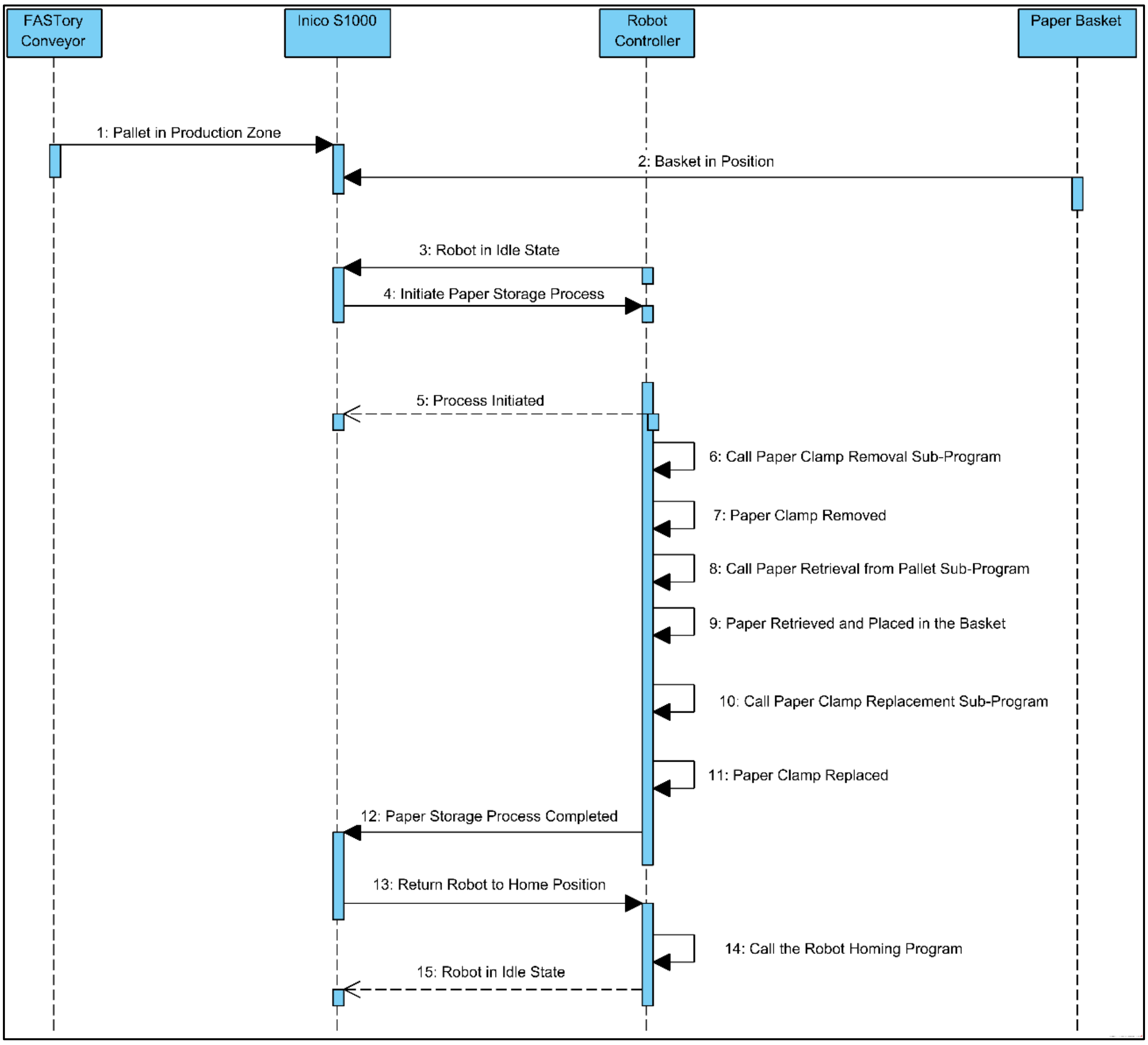


Figure 59 *Loading the paper to the Storage Basket from the Pallet (Sequence Diagram)*

The sequence of operations to be performed by the Dual-Arm station for loading the production papers from the pallet to the storage basket have a similar logic but with lesser active elements (paper feeder is not taken into consideration) as shown in Figure

59. When the process for removing the papers and storing them is initiated, , the RTU checks for the digital signals signifying that a pallet is present in the production zone ‘Z3’ of the FASTory conveyor (sensor output data) and the Robot Controller stating that the dual-arm manipulator is in the ‘idle’ state (Home position). Additionally, the presence of a paper basket in the Dual-Arm station is confirmed to the RTU, by means of proximity sensor data. When all of the conditions are met, the RTU invokes the Robot Controller to begin the paper storage process, and the Robot Controller changes its status from the ‘idle’ state to the ‘active’ state, and this is notified to the RTU. The Robot Controller calls for the ‘paper clamp removal’ sub-program and the left arm of the manipulator containing the dual cylinder parallel gripper, grasps the clamp and removes it. Then the ‘paper removal from the pallet sub-program is initiated and the right arm of the manipulator removes the paper from the pallet surface (with help from the pallet handling finger in the left arm, discussed in section 4.2.2) and delivers it to the paper storage basket. The ‘paper clamp replacement’ sub-program is then invoked and the left arm of the manipulator places the clamp back on to the pallet (unless another paper loading process is instantiated). The paper storing process (containing multiple sub-processes) is executed and the Robot Controller notifies the RTU of the current state of the system. The RTU then instructs the robot controller to return to the Home position and once the controller is in the ‘idle’ state, it generates a digital output to the RTU, signifying an end to the process.

4.2.2 Manipulator Behaviour and Interactions

This sub-section describes the interactions between the internal elements of the dual-arm robot and the FASTory conveyor, and their involvement in the handling of the pallets. The interactions are represented by Activity diagrams showcasing the actions performed by the individual arms and the base axis of the dual-arm manipulator. The diagrams represent the workflow of the process by breaking it down to the stepwise execution of individual actions.

The sequence of operations performed by the Dual-Arm station for loading of the production paper to the pallet from the storage rack is shown in Figure 60. Whereas, the sequence of operations for loading the paper to the storage basket from the pallet is shown in Figure 61.

The purpose of utilizing these diagrams is to document the inter-dependence of both the arms of the manipulator to perform the various sub-tasks in the main operation of handling the paper for loading/ storing. Especially when handling objects with unpredictable behaviours i.e. paper, the additional arm reduces the complication of tooling check Figure 61

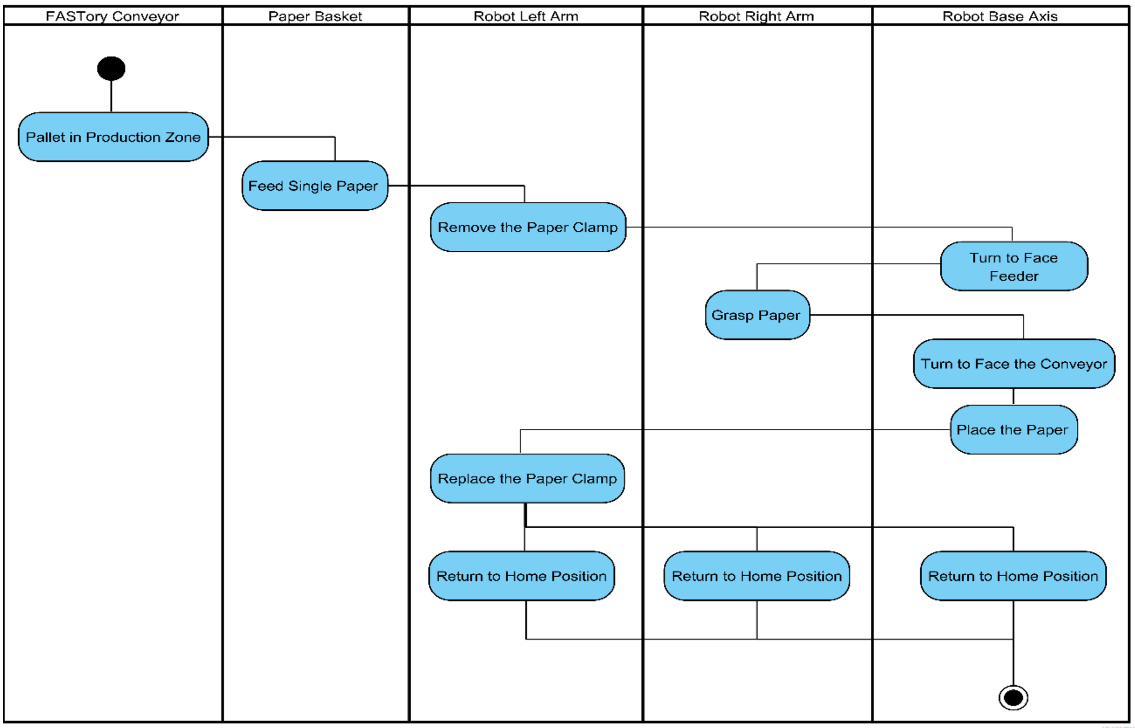


Figure 60 *Loading the paper to the pallet from the paper feeder (Activity Diagram)*

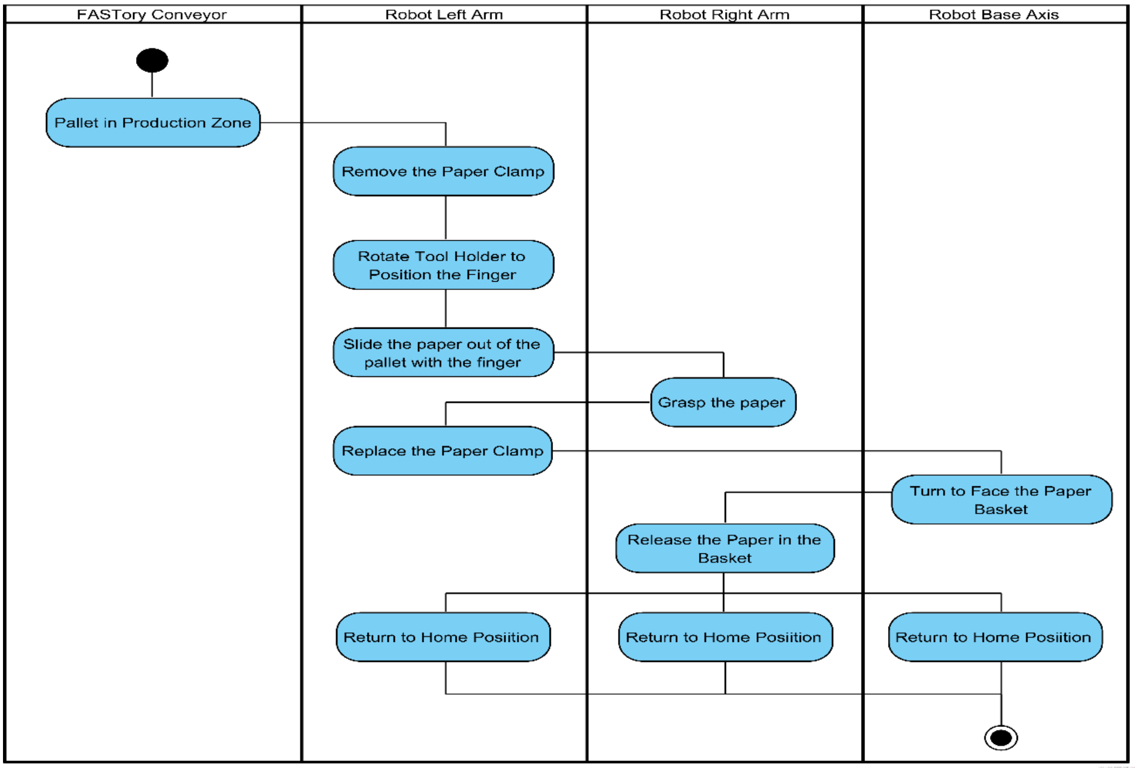


Figure 61 *Loading the paper to the Storage Basket from the Pallet (Activity Diagram)*

4.3 Handling of the Paper Baskets

The storage baskets are utilized to contain the papers containing the drawings of the mobile phone components. These baskets are supposed to hold all the papers for one complete batch of the symbolic production process. The Dual-Arm station is responsible for transferring the filled basket to the AMiR, which will take the drawn mobile phone models to the packaging station (Human-robot collaborative station) for individual box packaging. The Dual-Arm station must also receive empty boxes which are transferred back to it from the packaging station. The handling of the paper baskets is a fairly simple process where a parallel gripper (containing a specially designed finger grasps the basket and lock it in place) fitted on the right arm is sufficient to perform the basket handling operation.

This section of the chapter documents the behaviour of the system when the storage basket handling (Loading to the AMiR/ Retrieving from the AMiR) command is invoked by the Inico. However, this chapter differs from the previous two chapters as there is no special emphasis placed on the actions of the robot arms, as the process is simple and straightforward, requiring only one hand of the robot manipulator.

4.3.1 System Behaviour and Interactions

This sub-section describes the interactions between the various elements of the Dual-Arm station which are involved in the handling of the baskets. The interactions are represented by sequence diagrams to showcase the exchange of messages and system status data between the essential elements, which in these use cases are the Inico S1000, the Robot Controller, the Paper Basket and the AMiR.

The sequence of operations performed by the Dual-Arm station for the loading of the paper basket to AMiR from the Dual-Arm station is shown in Figure 62. Whereas, the sequence of operations for retrieving the paper basket from the AMiR and placing it in the designated location in the Dual-Arm station is shown in Figure 63.

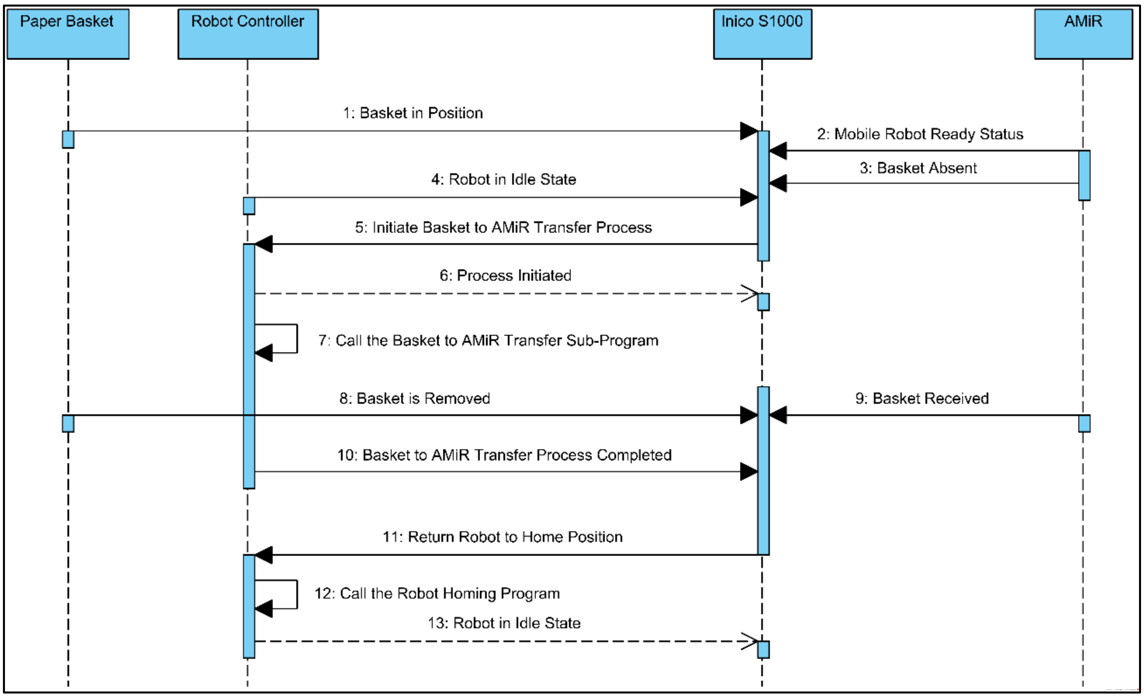


Figure 62 *Loading the Paper Basket to the AMiR (Sequence Diagram)*

When the process of loading the paper basket to the AMiR is initated, the RTU checks for the digital I/O signals which are inputted from the Dual-Arm station stating that the basket is in position; the status of the AMiR and it positional data and its capability to receive the basket is updated to the RTU by means of RESTful Web Services; and the Robot Controller if it is in the ‘idle’ state. Then the RTU invokes the manipulator to perform the paper basket loading process to the AMiR, from the Dual-Arm station and the state of the robot is changed to ‘idle from ‘active’. The Robot Controller calls the ‘Basket to AMiR Transfer’ sub-program and the parallel gripper in the right arm of the robot (same as the one used to handle the production paper) grasps and locks the basket in position and moves it to the designated target location in the AMiR. The Dual-Arm station and the AMiR update their status to the RTU, that the basket is removed through digital I/O output and that the basket is received through Web Services, respectively. After the ‘Basket to AMiR Transfer’ sub-program is completed, the robot updates the RTU about the current state of the system. The RTU then instructs the robot controller to return to the Home position and once the controller is in the ‘idle’ state, it generates a digital output to the RTU, signifying an end to the process.

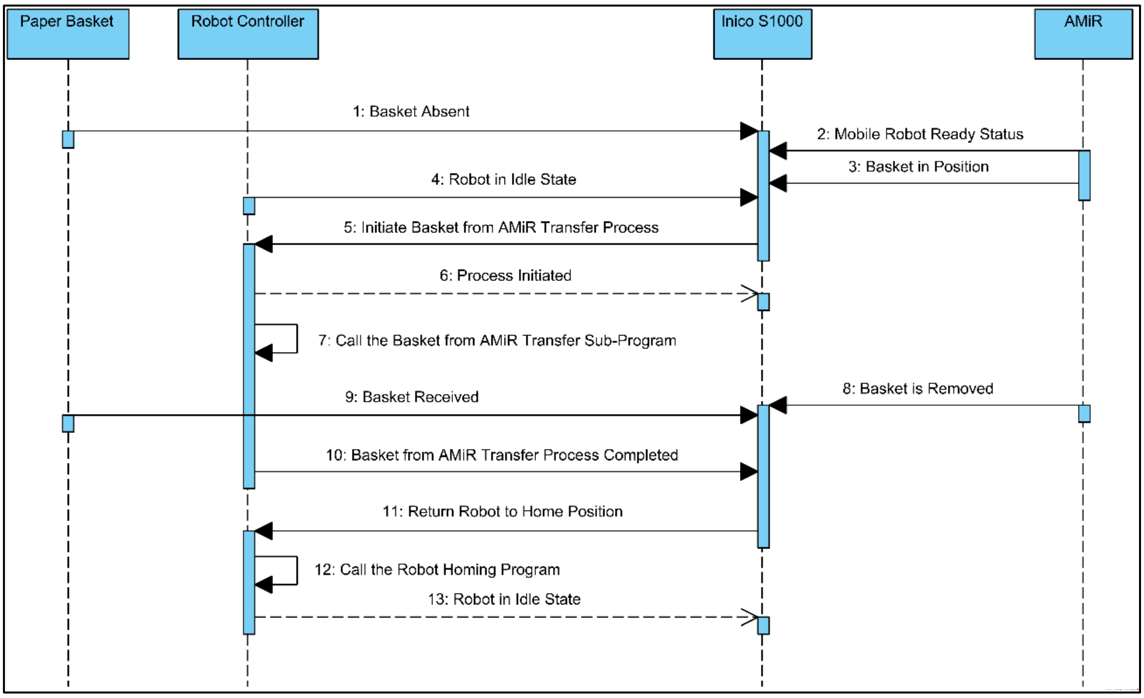


Figure 63 *Retrieving the Paper Basket from the AMiR (Sequence Diagram)*

When the process of Retrieving the paper basket from the AMiR is initated, the RTU checks for the digital I/O signals which are inputted from the Dual-Arm station stating that the basket is absent; the status of the AMiR and it positional data and its capability to deliver the basket is updated to the RTU by means of RESTful Web Services; and the Robot Controller if it is in the 'idle' state. Then the RTU invokes the manipulator to perform the paper basket retrieval process from the AMiR, to the Dual-Arm station and the state of the robot is changed to 'idle from 'active'. The Robot Controller calls the 'Basket from AMiR Transfer' sub-program and the parallel gripper in the right arm of the robot (same as the one used to handle the production paper) grasps and locks the basket in position and moves it to the designated target location in the Dual-Arm station. The Dual-Arm station and the AMiR update their status to the RTU, that the basket is received through digital I/O output and that the basket is removed through Web Services, respectively. After the 'Basket from AMiR Transfer' sub-program is completed, the robot updates the RTU about the current state of the system. The RTU then instructs the robot controller to return to the Home position and once the controller is in the 'idle' state, it generates a digital output to the RTU, signifying an end to the process.

5. CONCLUSION

The primary objective behind the ideation of this thesis is to improve the functionality of the FASTory line and to streamline the operation flow. The idea of the concept to merge the process capabilities of the Buffer Cell and the Main Cell, by upgrading the existing robot manipulators and the other production elements in the cell, with a single dual-arm manipulator. Furthermore, this thesis aims to make it possible to further expand the scope of the FASTory line by merging it with the other isolated intelligent systems in the lab, thereby, creating a larger interconnected system with added process capabilities.

The work involved in this thesis implementation began with the selecting of the appropriate model of the dual-arm manipulator, to be capable of handling the process requirements with provisions to handle future modifications, updates and improvements. The Yaskawa SDA10F manipulator currently being implemented has a higher payload handling capacity and reachability (when compared with the originally considered SDA5F) and offers leeway when making consideration while designing the End of Arm Tooling concepts. Moreover, it is amenable to changes and future expansions because of the higher payload capacity and reachability. This turned out to be prudent decision, as the dual-arm robot is being utilized to handle deformable linear objects (DLOs) for the project ‘REMODEL’ of the Horizon 2020 Program.

The feasibility of this implementation had to be verified virtually before making the physical execution, because performing the physical execution without fully understanding the behaviour of the manipulator with the elements in the FASTory line has a higher chance of it requiring additional modifications and corrections, made to the original installation. Hence the station was modelled and multiple changes were made over several iterations as explained in section 3.2. The cell is capable of housing the robot and the other essential elements of both the Buffer Cell and Main Cell. It is currently called the Dual-Arm station, and has additional elements which are unique to it.

The tooling system for the dual-arm robot was conceptualized and designed to be simple, cost-efficient, and resourceful, and perform the required operations of the robot. An additional criteria which was considered while making the tooling considerations was to demonstrate the synchronized dual-arm manipulation of the objects. This enabled the tooling to be simple, yet capable of handling of the significant numbers of objects having diverse characteristics and handling requirements.

The modelled cell and all its associated elements were imported into the simulation environment of the robot manipulator. The Robot Controller was virtually installed in the cell and the dual-arm manipulator was positioned in the imported cell. The reachability of the manipulator was determined and the cell design was finalized. The sequence of operations and the interactions made by the manipulator were modelled as diagrams.

The physical FASTory line in the lab so far, has had the existing Main Cell structure and all its elements including the manipulator, additional conveyor, vision system, etc. removed. The original plate on which the SCARA was mounted has been cut and modified to hold the dual-arm manipulator. The tool holder along with the pallet handling finger are installed.

5.1 Future Works

The timeline for this thesis implementation was incorrectly estimated and the defined scopes had to be altered towards the later stages of the thesis progression. This resulted in the allocation of time for completing tasks which were not considered as high priority in the currently fixed scope. More time was spent on creating standardized design drawings for the created models of the tools for fabrication, the physical dismantling of the cell and the modifications to the station in which the robot is mounted, setting up the license for the simulation environment, etc. However, these tasks are documented as future work and will be subsequently implemented by me.

- Creating the programs for the process simulation in the MotoSim environment and placing an emphasis on setting up soft limits for the robot and collision detection.
- Physical construction of the Dual-Arm station and the reinstallation of the manipulator along with setting up of the remainder of the tooling is required. The robot program from the simulation is to be transferred to the physical controller and the offsets have to be fixed. Safety protocols are to be established and physical fencing to separate the manipulator from the outside is to be set up.
- Integrate the dual-arm manipulator with the RTU of the work station and update the OKD-MES of the FASTory, to handle the APIs for handling the station (after developing them).
- Provision for the easy and modular installation of other tooling, so that the manipulator could be utilized for experimenting in the project ‘REMODEL’ for the Horizon 2020 Program.

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